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(54) **OPTICAL FIBER PRESSURE SENSOR GUIDEWIRE**

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(73) Assignee: **Vascular Imaging Corporation**, Rancho Cordova, CA (US)

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Related U.S. Application Data

(60) Provisional application No. 61/791,486, filed on Mar. 15, 2013, provisional application No. 61/753,221, filed on Jan. 16, 2013, provisional application No. 61/709,781, filed on Oct. 4, 2012, provisional application No. 61/659,596, filed on Jun. 14, 2012, provisional application No. 61/651,832, filed on May 25, 2012.

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A61B 5/00 (2006.01)

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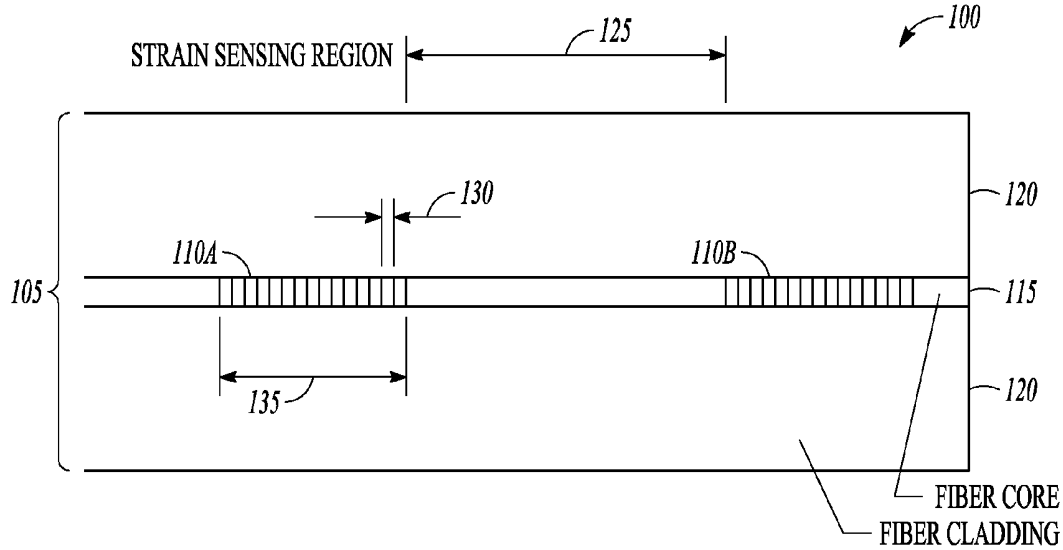
CPC ***A61B 5/02154*** (2013.01); ***A61B 5/0084*** (2013.01); ***A61B 5/6851*** (2013.01)
USPC **600/478**

(57) **ABSTRACT**

In an example, this document discloses an apparatus for insertion into a body lumen, the apparatus comprising an optical fiber pressure sensor. The optical fiber pressure sensor comprises an optical fiber configured to transmit an optical sensing signal, a temperature compensated Fiber Bragg Grating (FBG) interferometer in optical communication with the optical fiber, the FBG interferometer configured to receive a pressure and modulate, in response to the received pressure, the optical sensing signal, and a sensor membrane in physical communication with the FBG interferometer, the membrane configured to transmit the received pressure to the FBG interferometer.



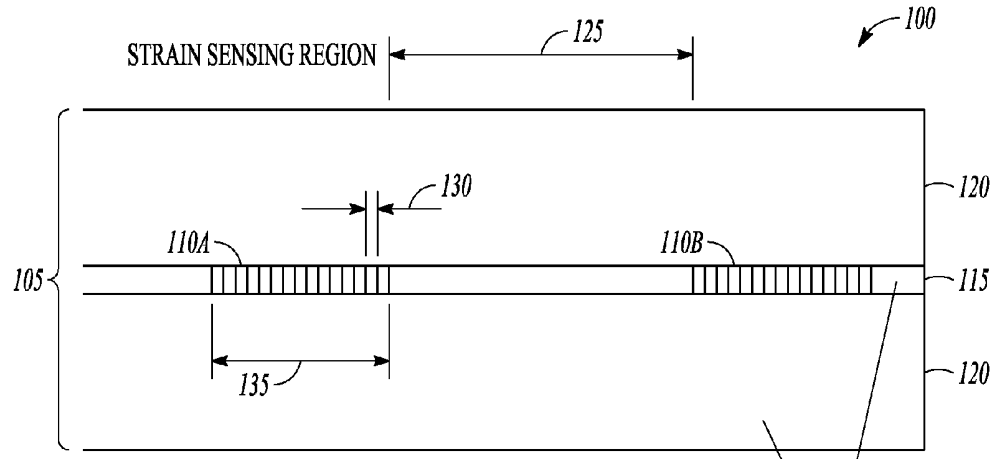


FIG. 1

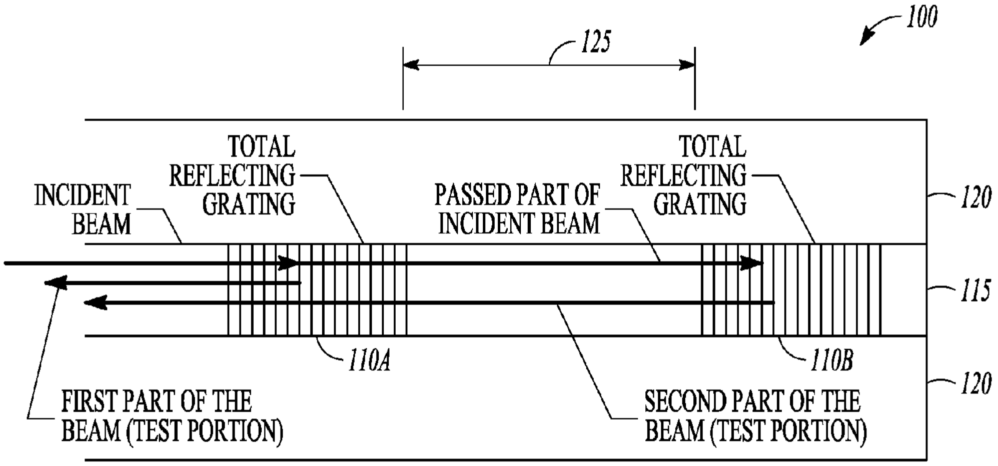


FIG. 2

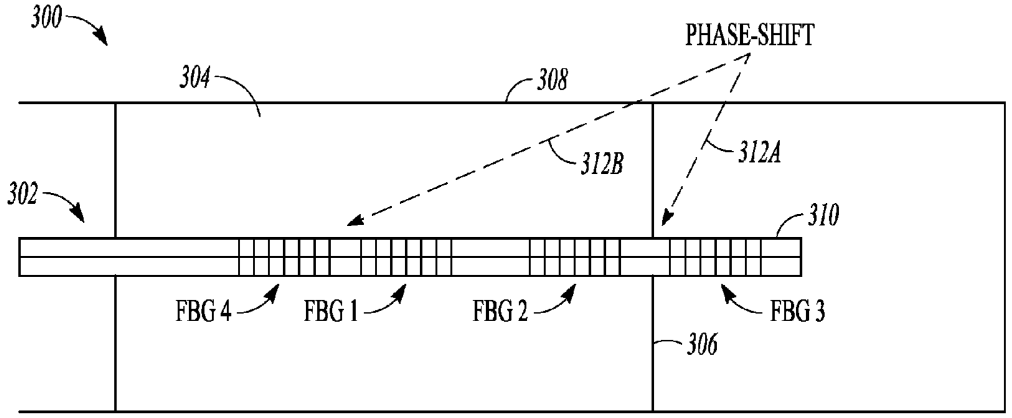


FIG. 3

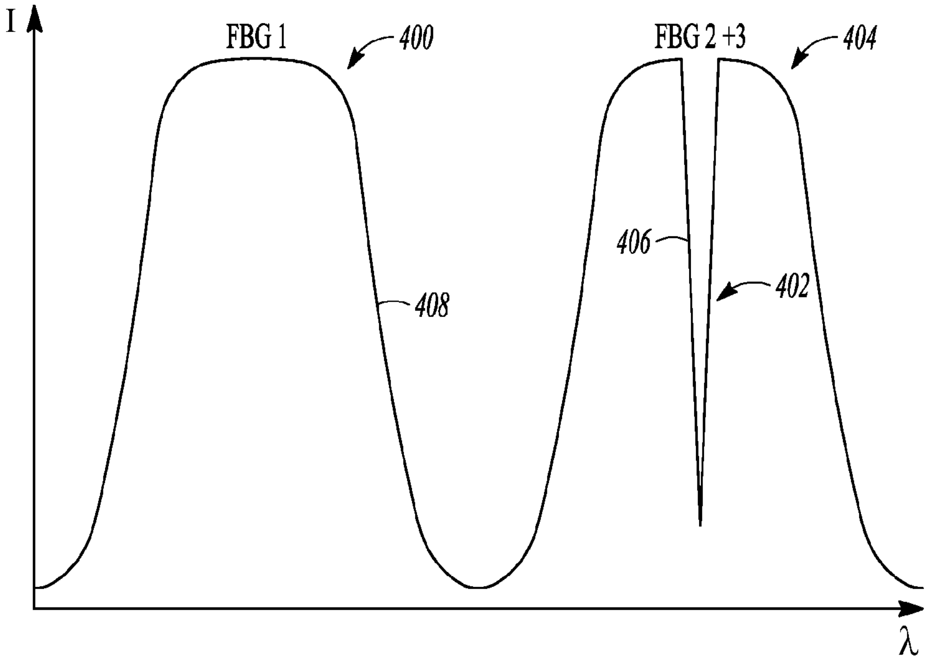

I
FBG 1
400
FBG 2 +3
404
406
402
408
λ

FIG. 4A

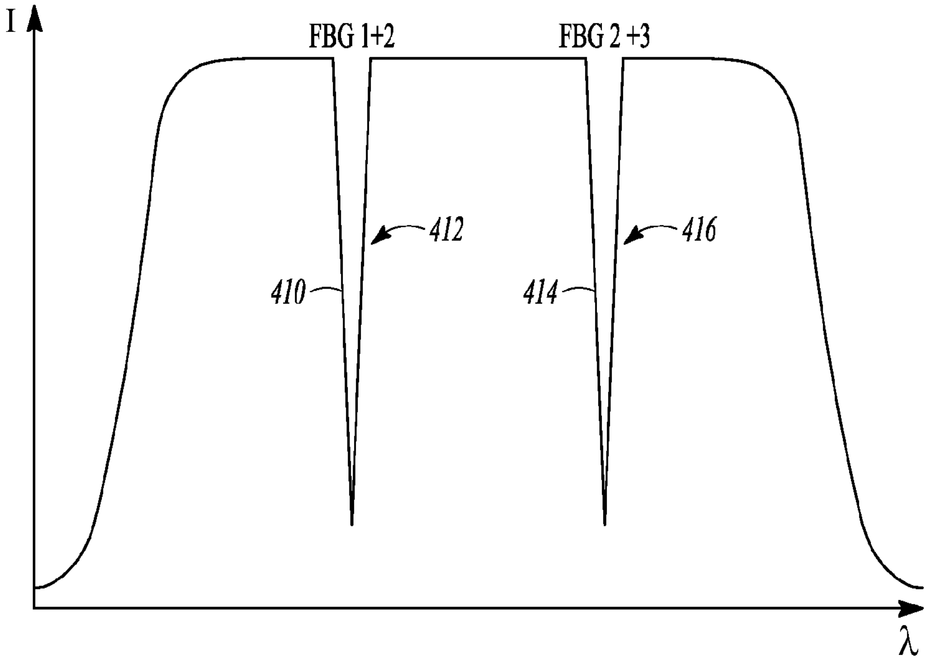

I
FBG 1+2
FBG 2 +3
412
416
410
414
λ

FIG. 4B

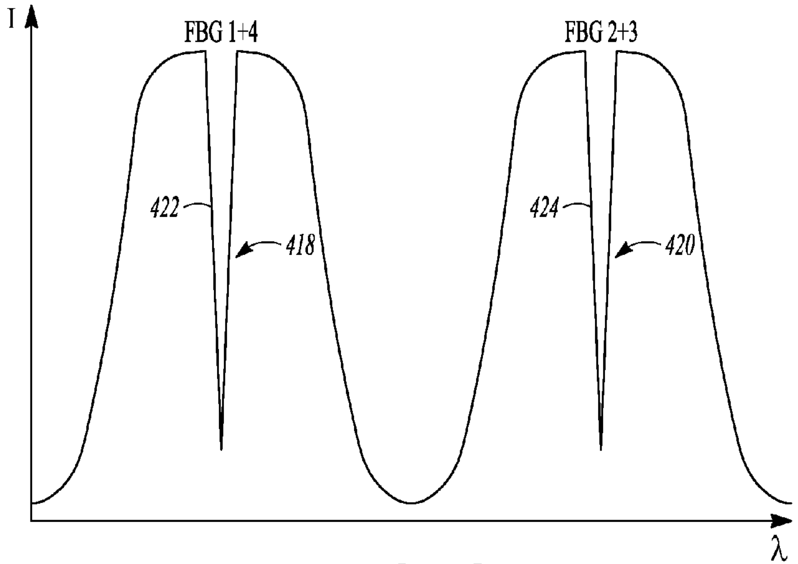

I
FBG 1+4
FBG 2+3
422
418
424
420
λ

FIG. 4C

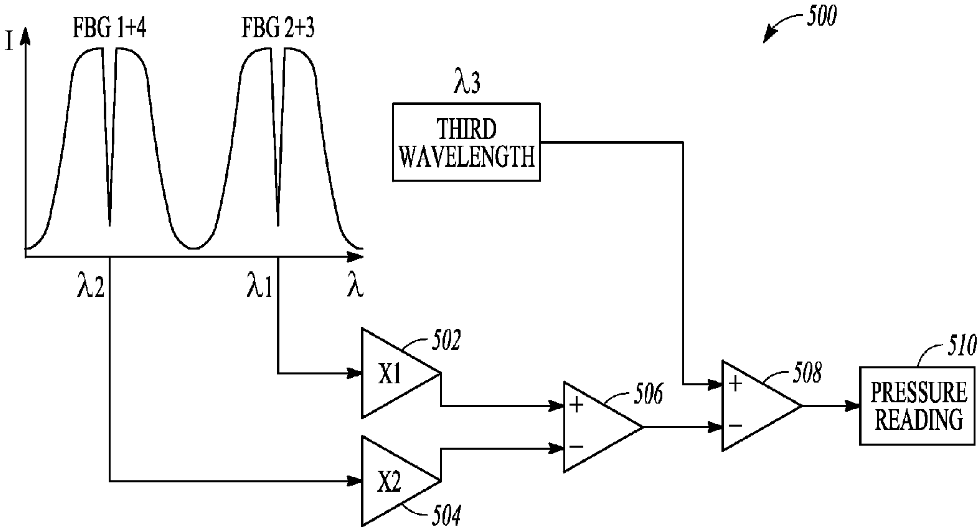

500
I
FBG 1+4
FBG 2+3
λ2
λ1
λ
λ3
THIRD WAVELENGTH
502
X1
X2
504
506
+
−
508
+
−
510
PRESSURE READING

FIG. 5

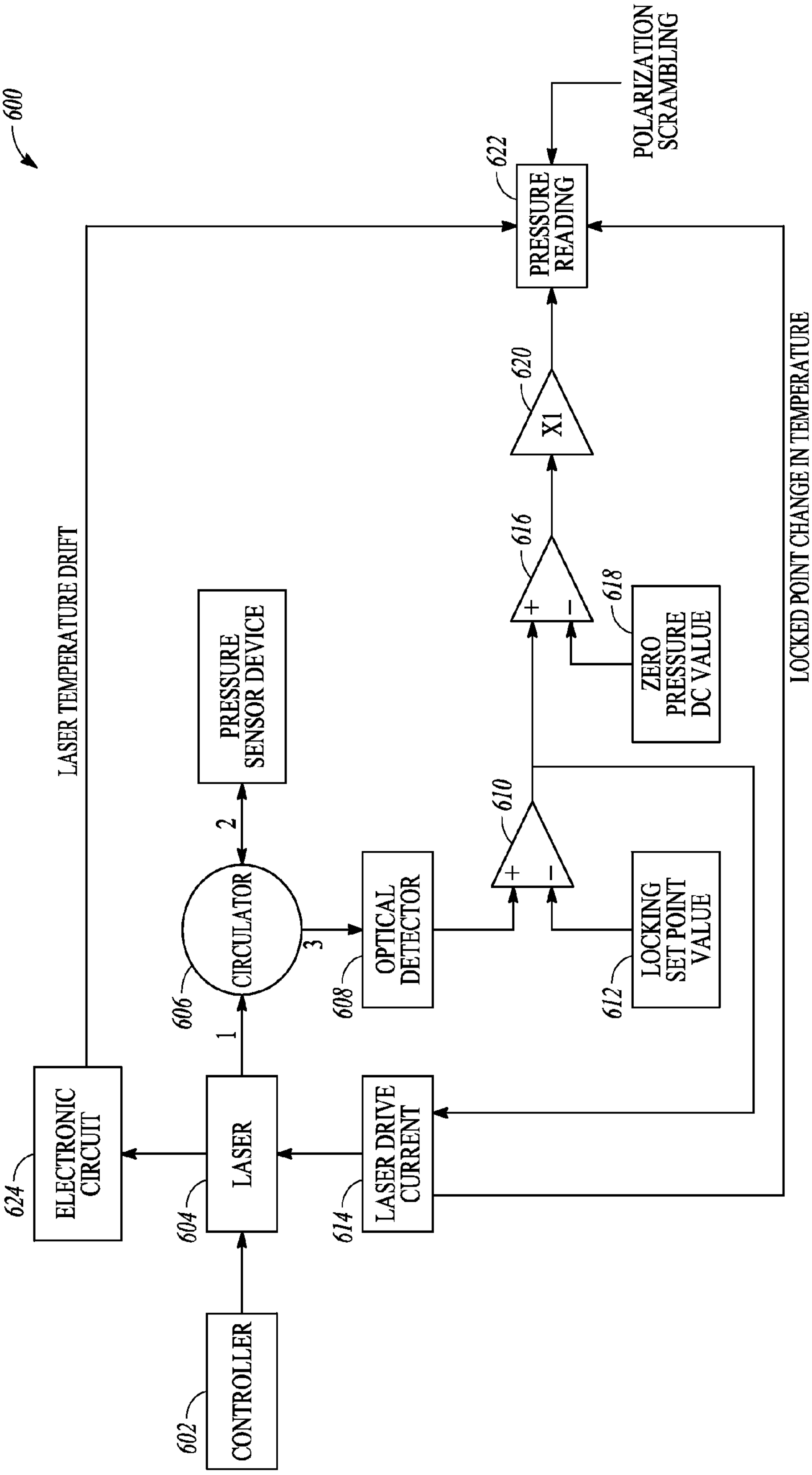

600
CONTROLLER
602
LASER
604
ELECTRONIC CIRCUIT
624
LASER DRIVE CURRENT
614
CIRCULATOR
606
1
2
3
PRESSURE SENSOR DEVICE
OPTICAL DETECTOR
608
LOCKING SET POINT VALUE
612
610
+
−
ZERO PRESSURE DC VALUE
618
616
+
−
X1
620
PRESSURE READING
622
POLARIZATION SCRAMBLING
LASER TEMPERATURE DRIFT
LOCKED POINT CHANGE IN TEMPERATURE

FIG. 6A

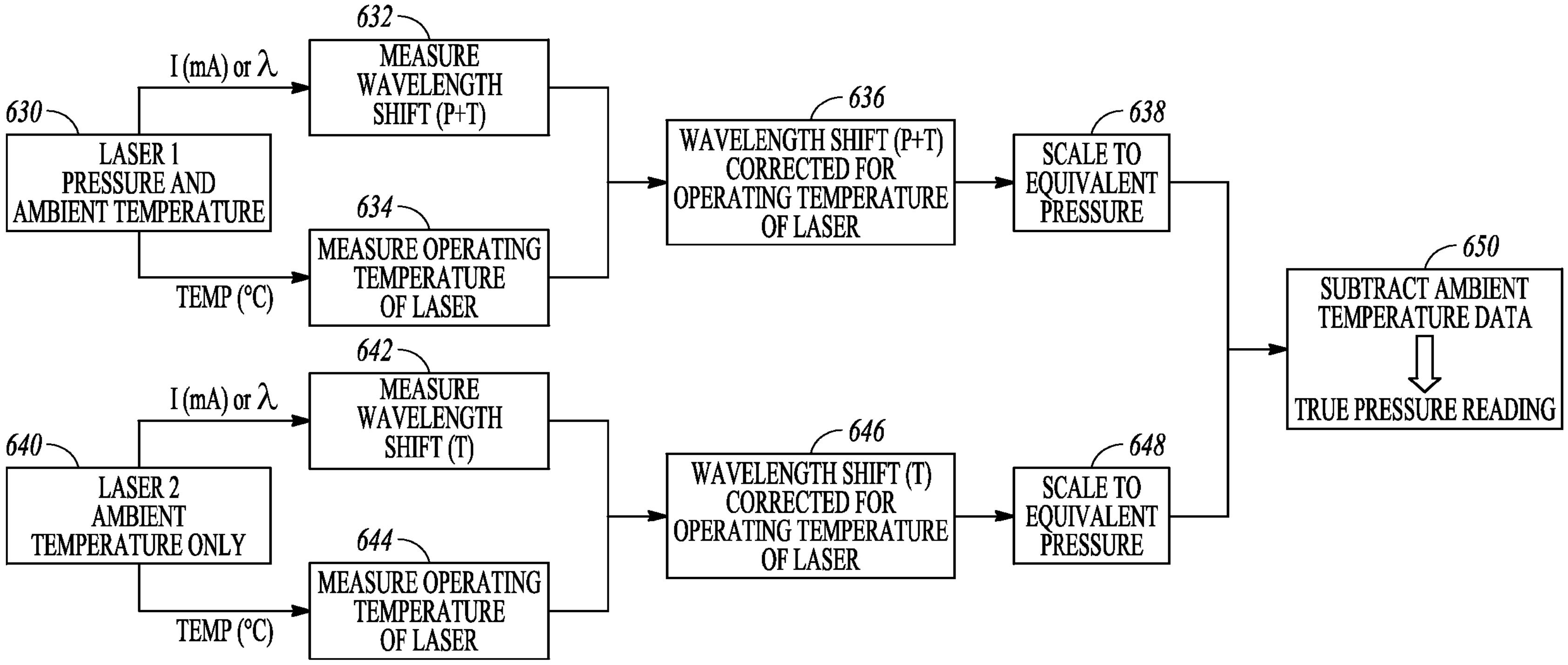

630
LASER 1
PRESSURE AND
AMBIENT TEMPERATURE
I (mA) or λ
TEMP (°C)
632
MEASURE
WAVELENGTH
SHIFT (P+T)
634
MEASURE OPERATING
TEMPERATURE
OF LASER
636
WAVELENGTH SHIFT (P+T)
CORRECTED FOR
OPERATING TEMPERATURE
OF LASER
638
SCALE TO
EQUIVALENT
PRESSURE
640
LASER 2
AMBIENT
TEMPERATURE ONLY
I (mA) or λ
TEMP (°C)
642
MEASURE
WAVELENGTH
SHIFT (T)
644
MEASURE OPERATING
TEMPERATURE
OF LASER
646
WAVELENGTH SHIFT (T)
CORRECTED FOR
OPERATING TEMPERATURE
OF LASER
648
SCALE TO
EQUIVALENT
PRESSURE
650
SUBTRACT AMBIENT
TEMPERATURE DATA
TRUE PRESSURE READING

FIG. 6B

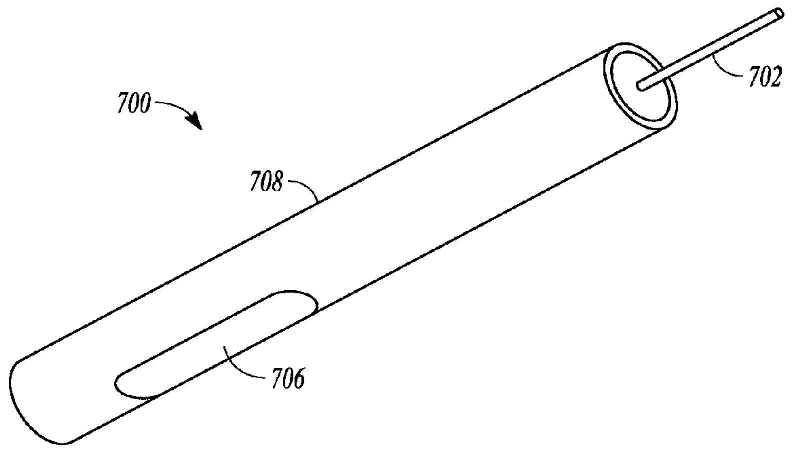


FIG. 7A

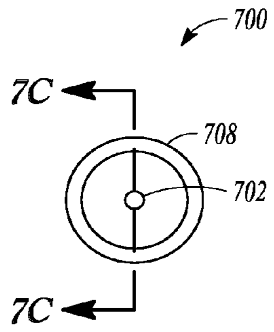


FIG. 7B

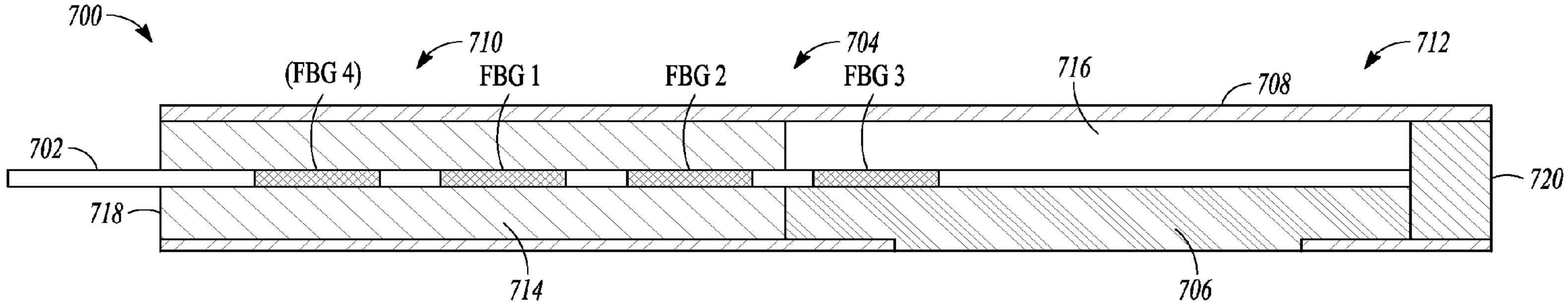


FIG. 7C

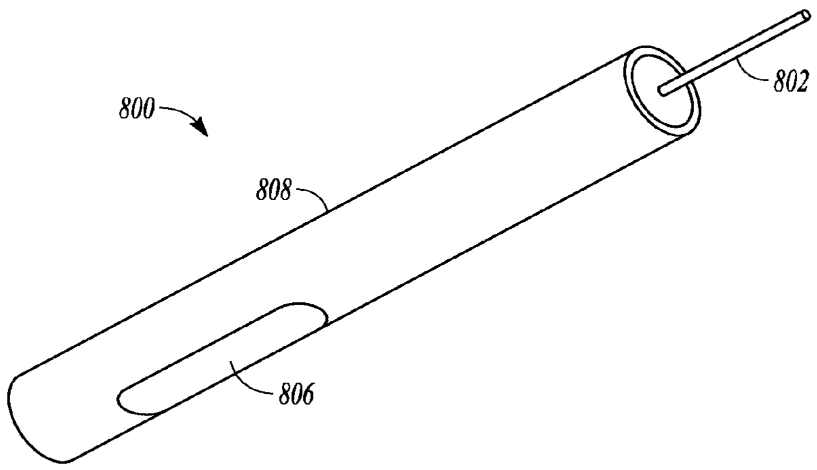


FIG. 8A

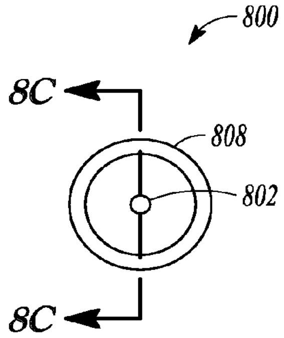


FIG. 8B

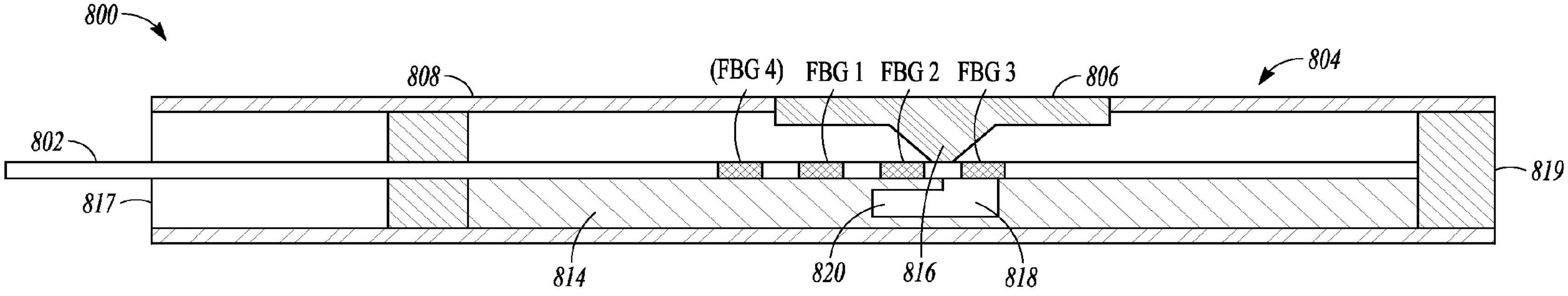


FIG. 8C

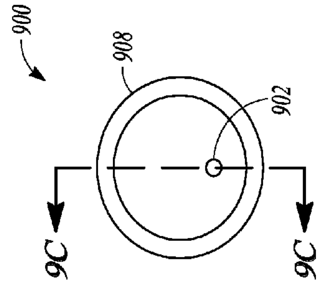


FIG. 9B

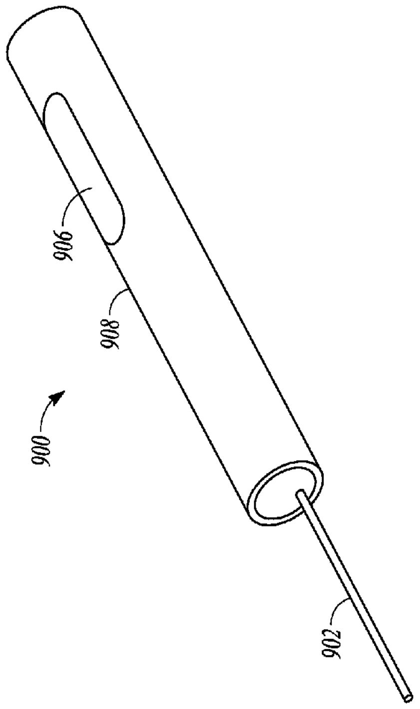


FIG. 9A

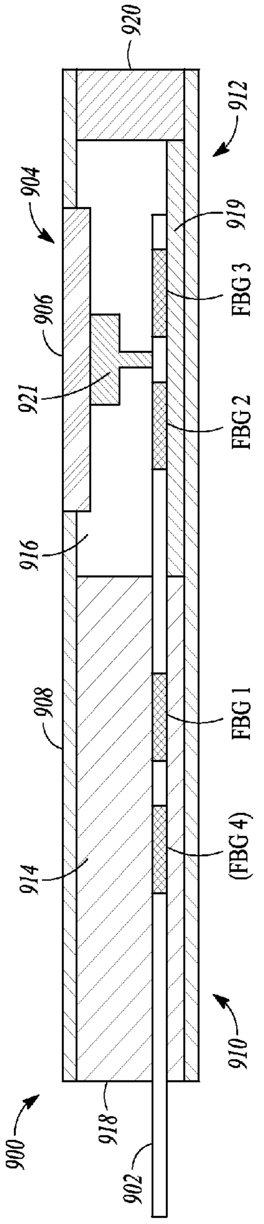


FIG. 9C

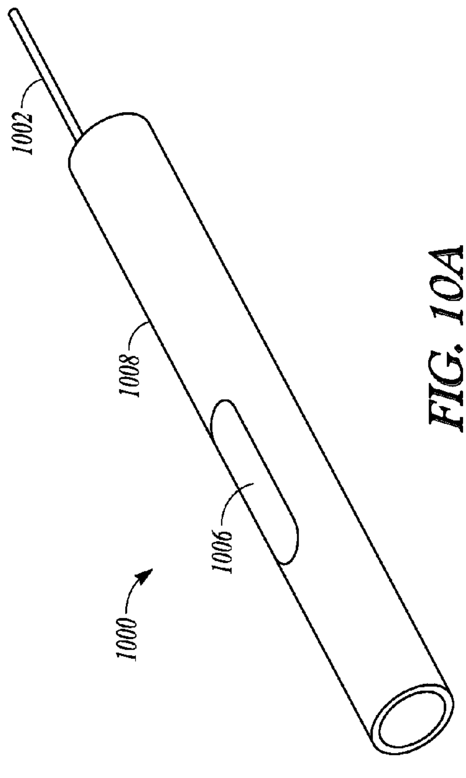


FIG. 10A

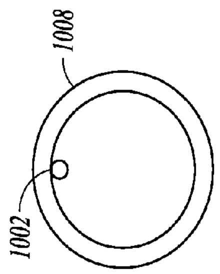


FIG. 10B

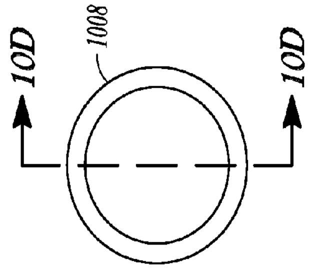


FIG. 10C

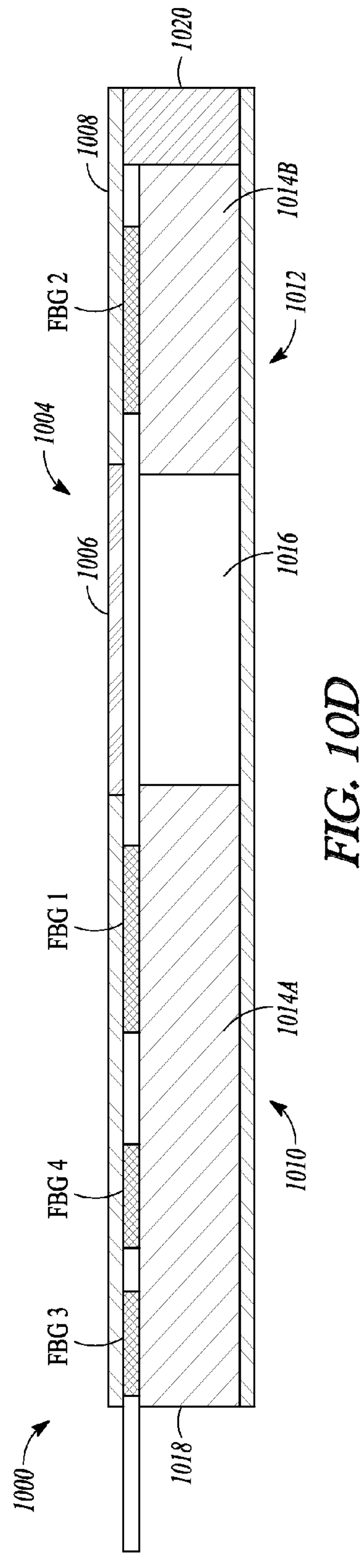


FIG. 10D

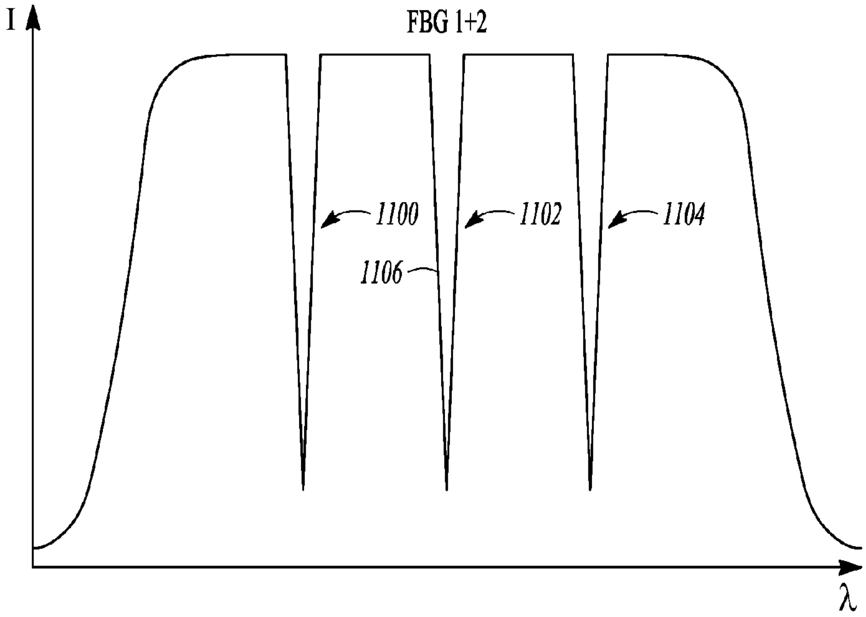


FIG. 11

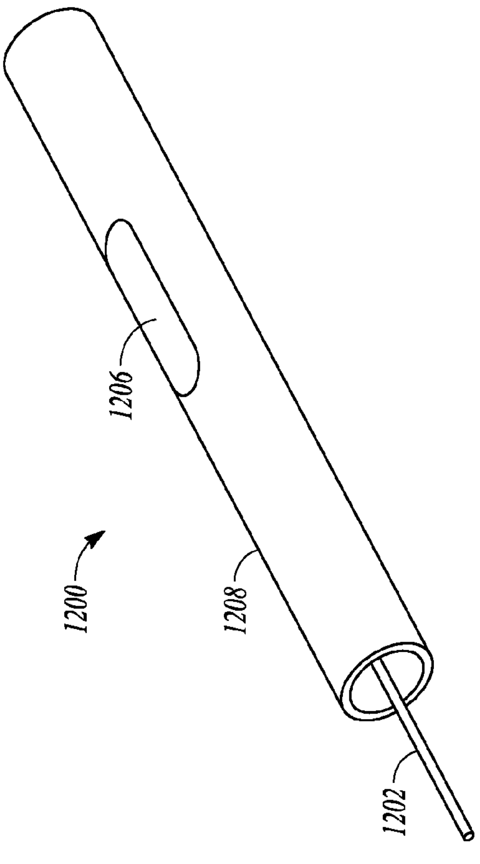


FIG. 12A

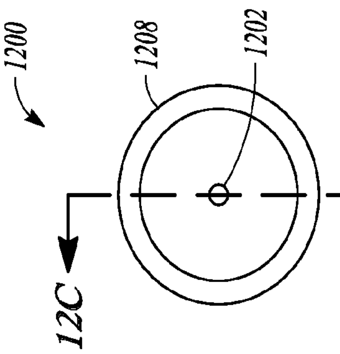


FIG. 12B

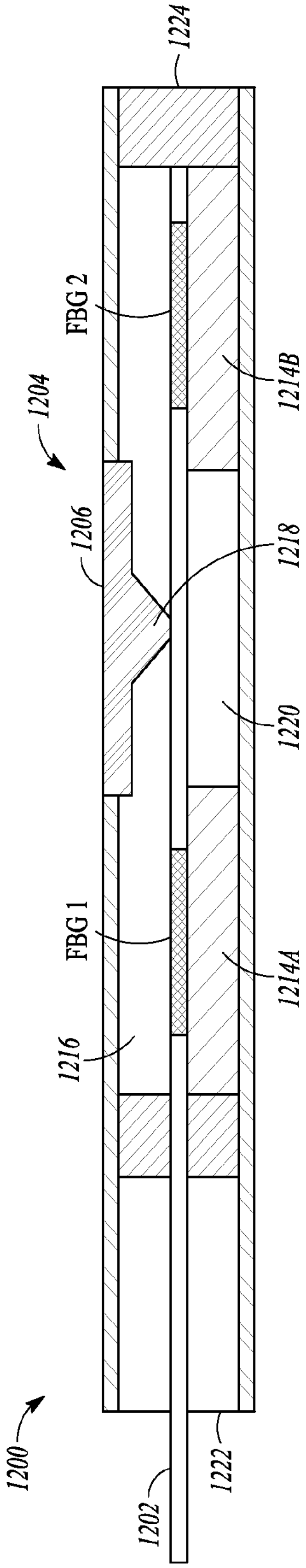


FIG. 12C

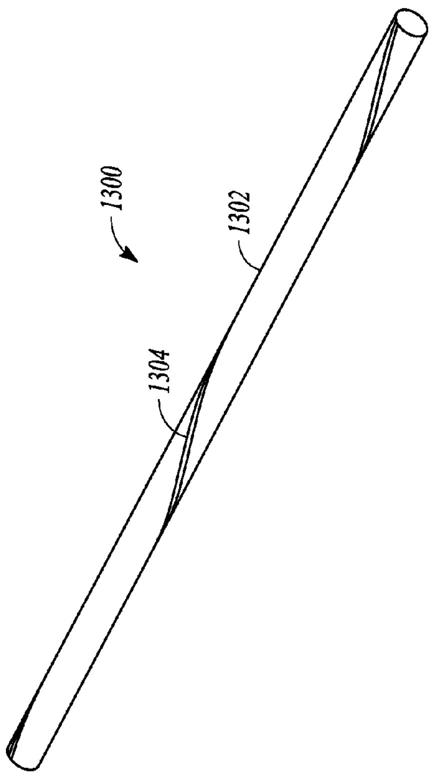


FIG. 13A

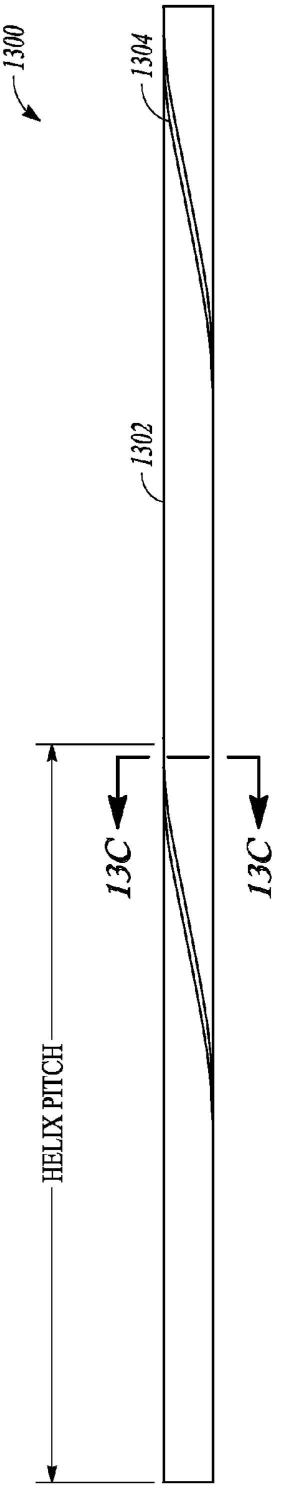


FIG. 13B

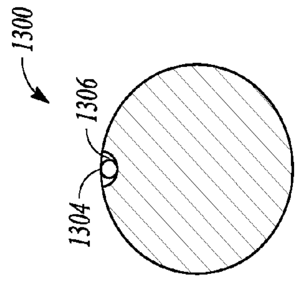


FIG. 13C

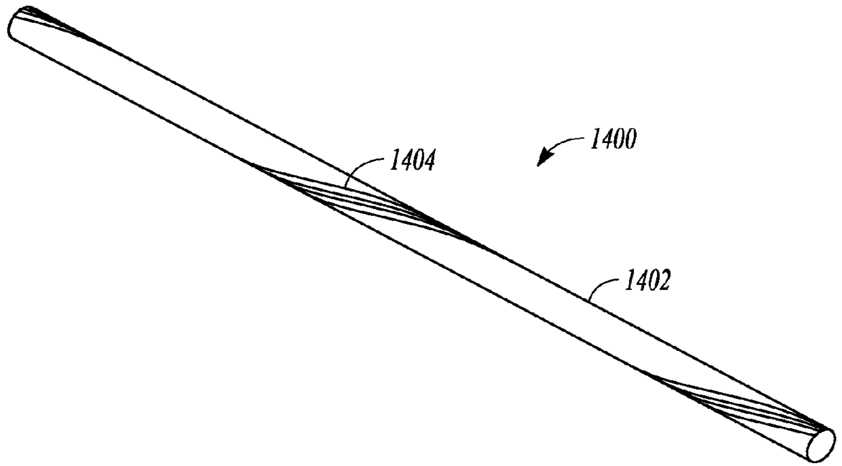


FIG. 14A

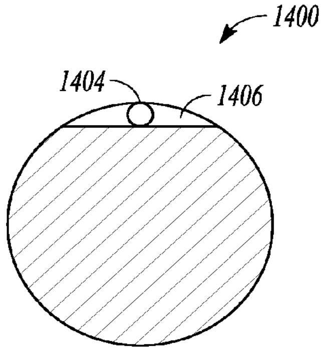


FIG. 14C

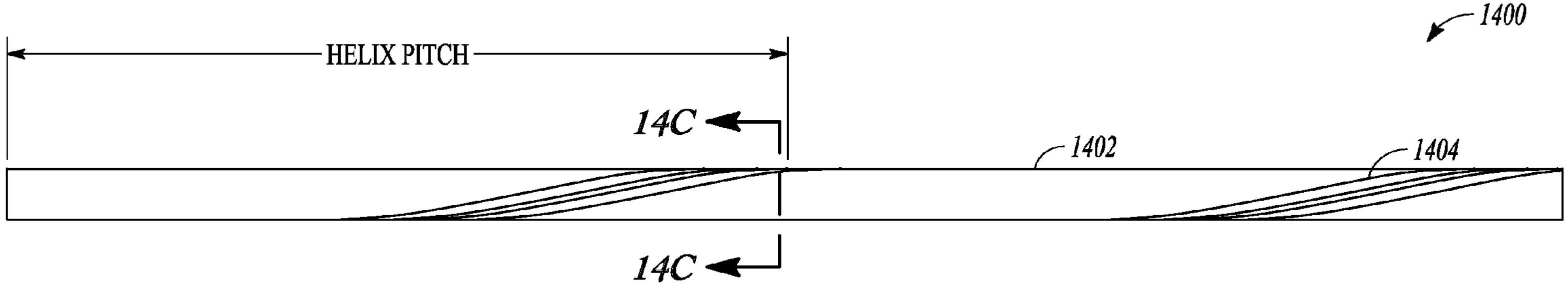


FIG. 14B

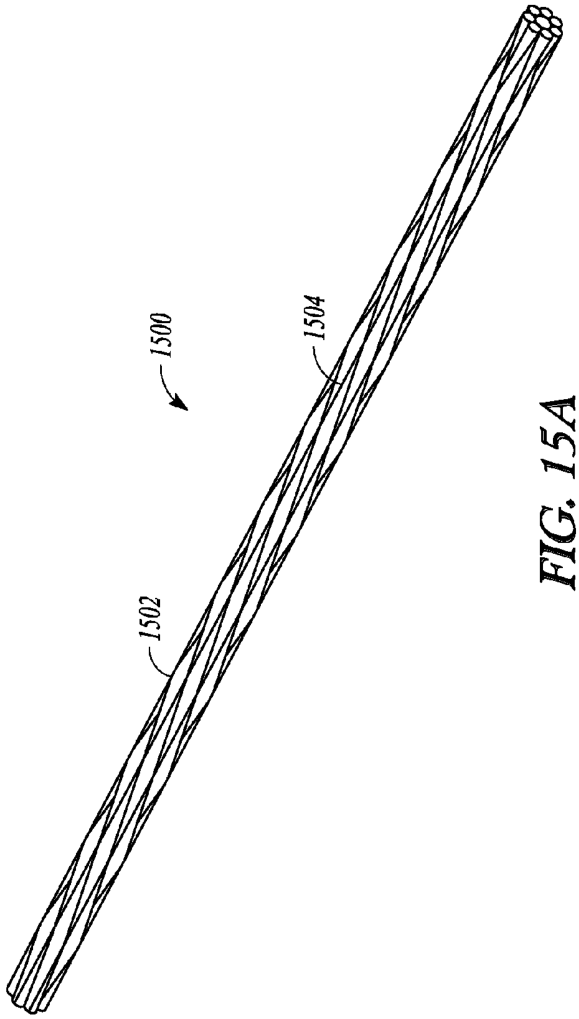


FIG. 15A

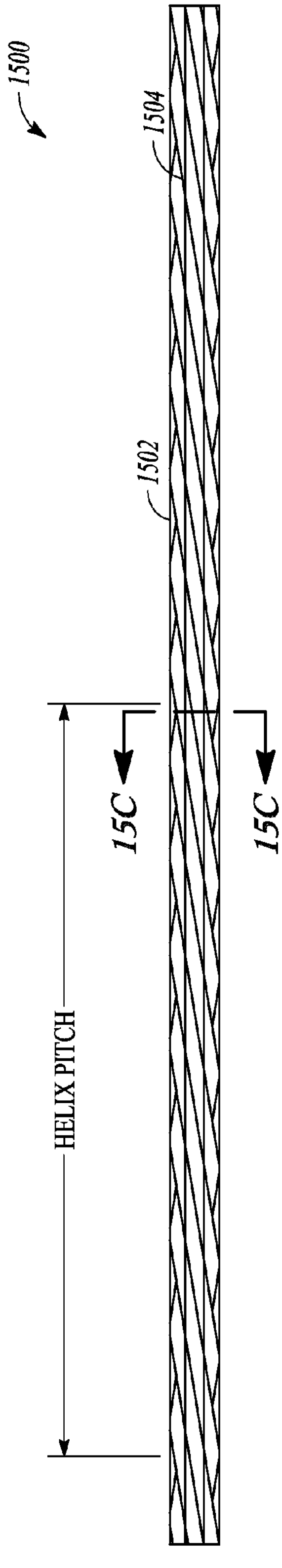


FIG. 15B

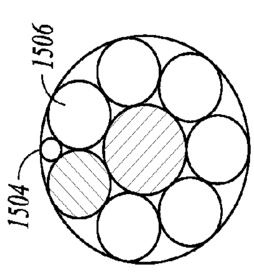


FIG. 15C

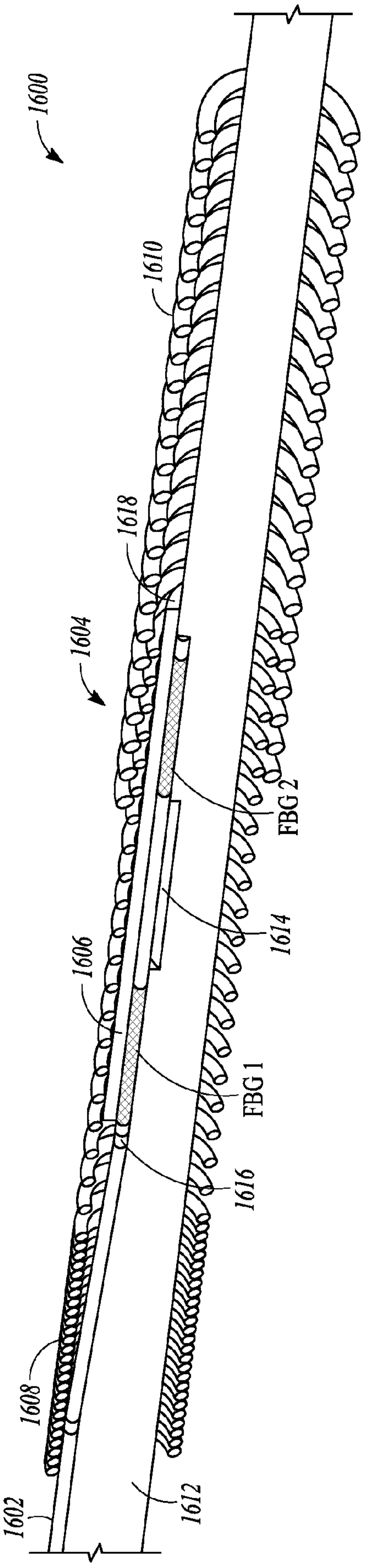


FIG. 16

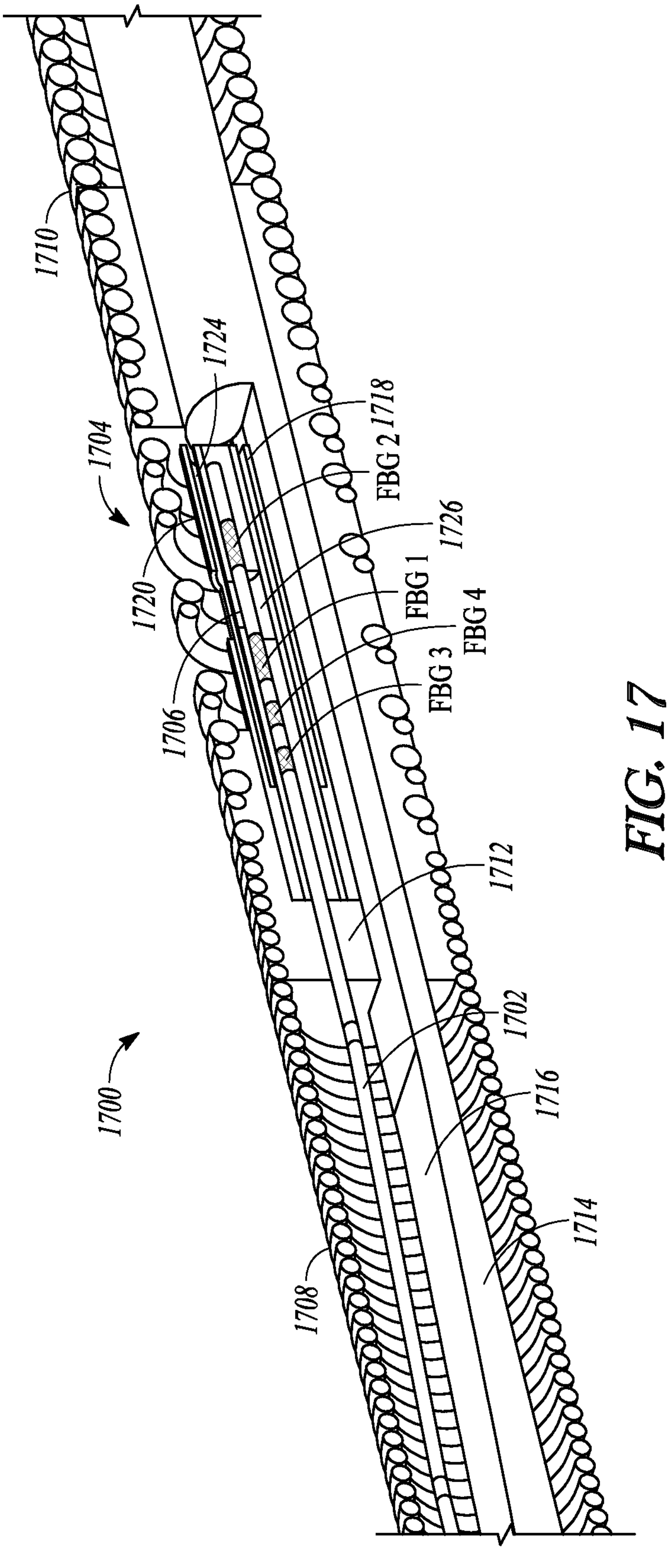

1710
1724
1704
1718
FBG 2
1726
FBG 1
FBG 4
FBG 3
1720
1706
1712
1702
1716
1700
1714
1708

FIG. 17

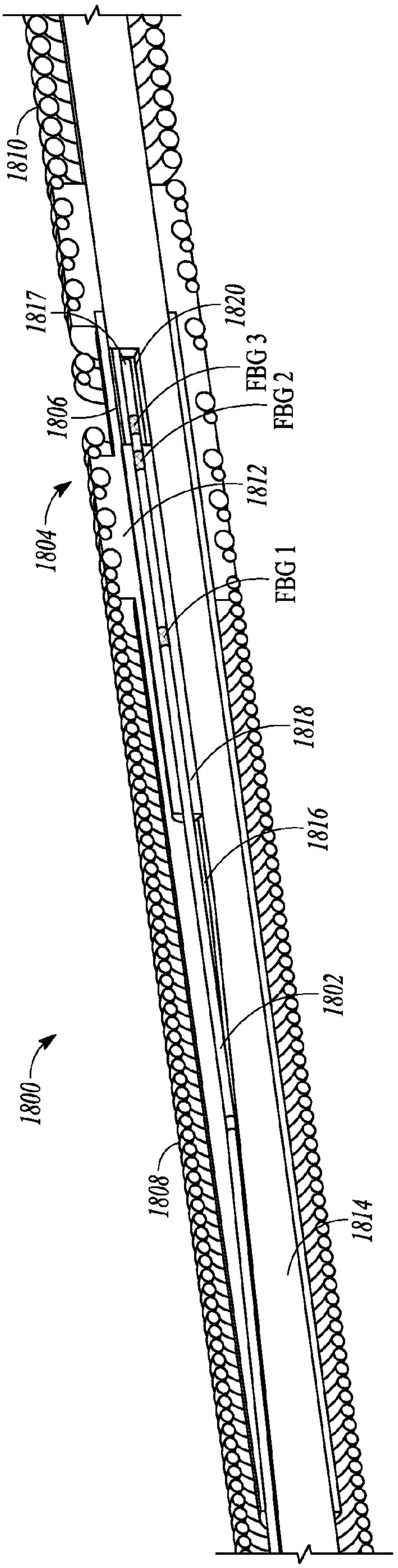

1810
1817
1806
1820
FBG 3
FBG 2
1812
1804
FBG 1
1818
1816
1802
1800
1808
1814

FIG. 18

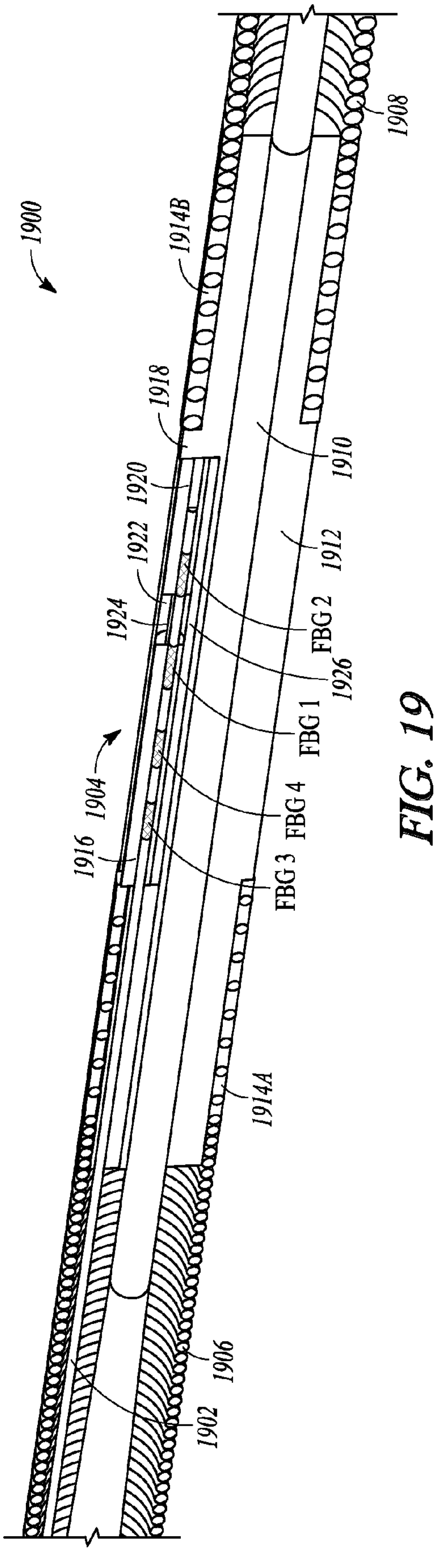

1900
1914B
1908
1918
1910
1920
1922
1912
1924
FBG 2
1926
FBG 1
1904
FBG 4
1916
FBG 3
1914A
1906
1902

FIG. 19

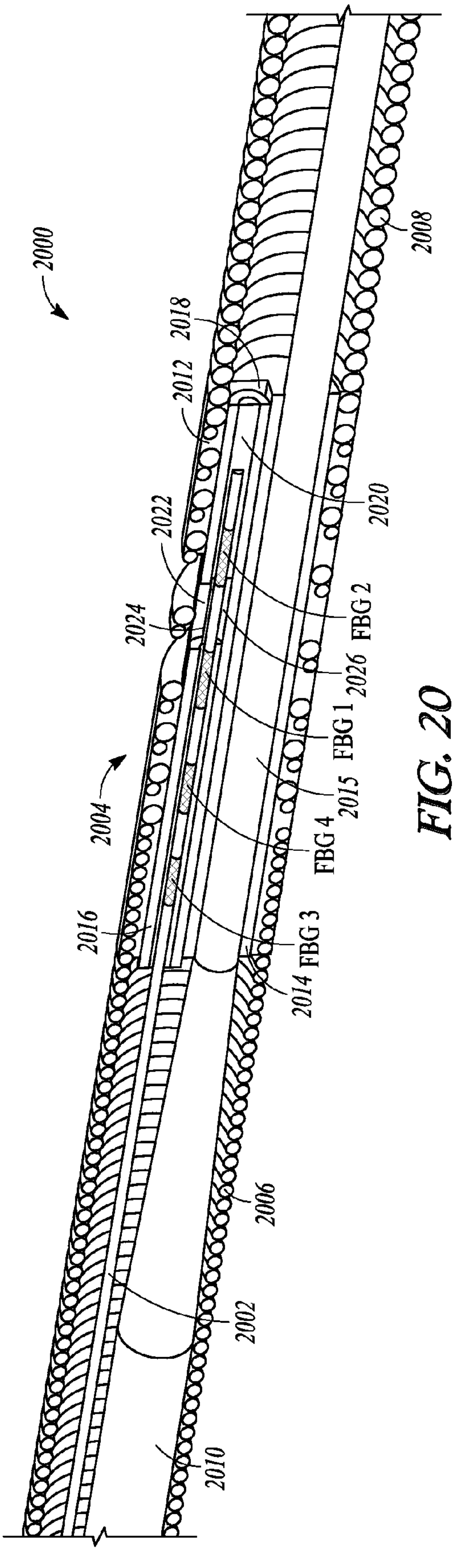

2000
2018
2012
2008
2020
2022
2024
FBG 2
2026
FBG 1
2004
2015
FBG 4
2016
FBG 3
2014
2006
2002
2010

FIG. 20

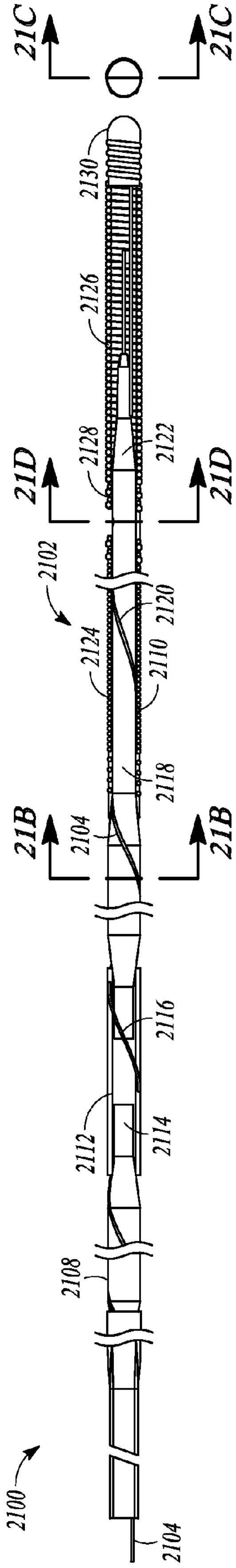


FIG. 21A

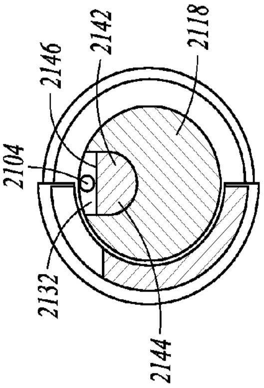


FIG. 21D

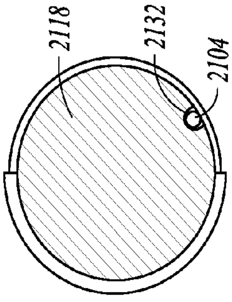


FIG. 21B

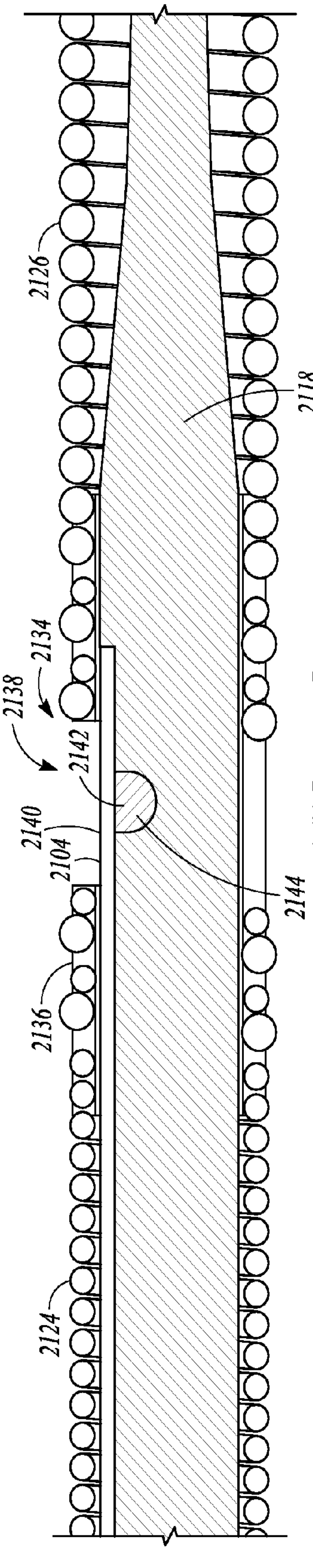


FIG. 21C

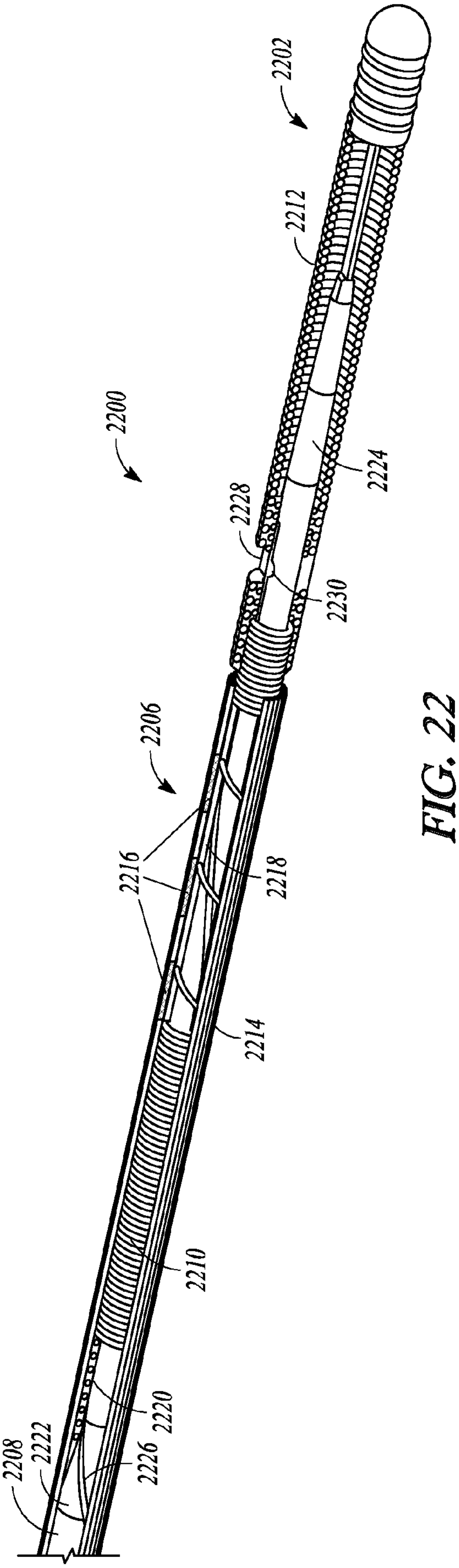

2202
2212
2200
2224
2228
2230
2206
2216
2218
2214
2210
2220
2208
2222
2226

FIG. 22

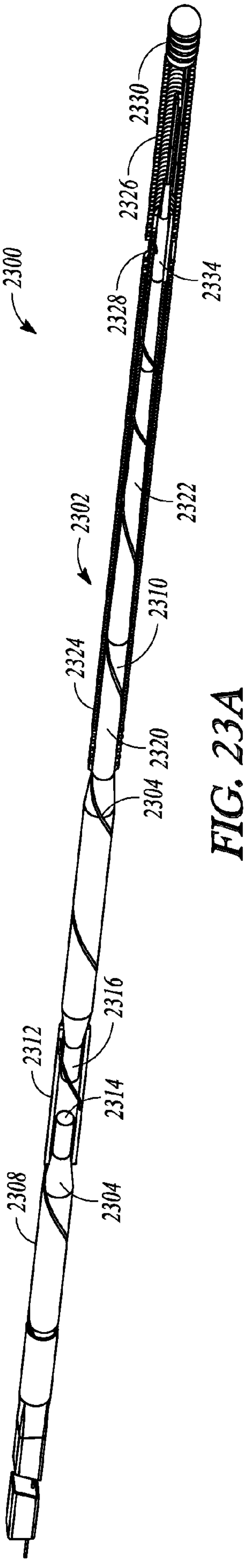


FIG. 23A

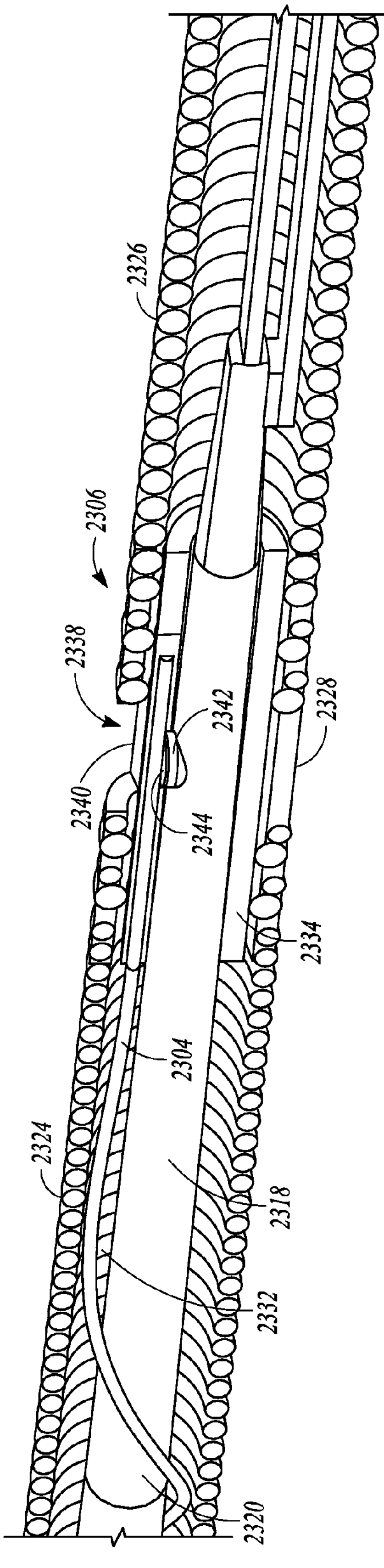


FIG. 23B

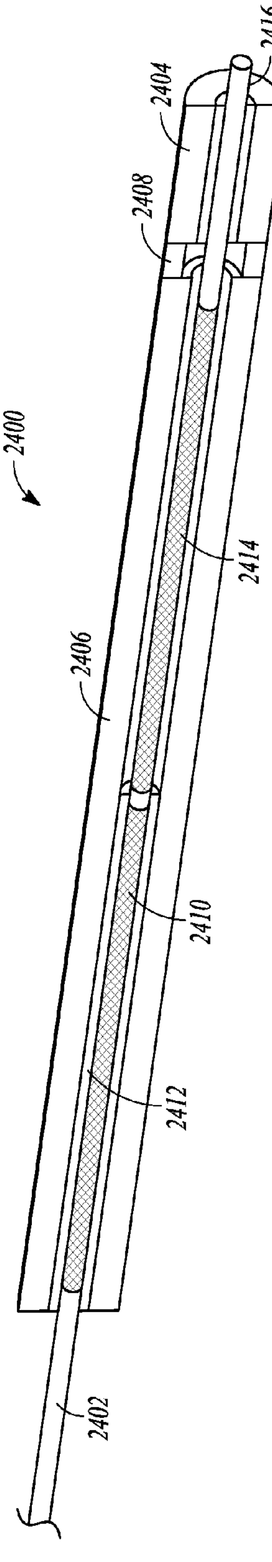

2400
2416
2404
2408
2406
2414
2410
2412
2402

FIG. 24

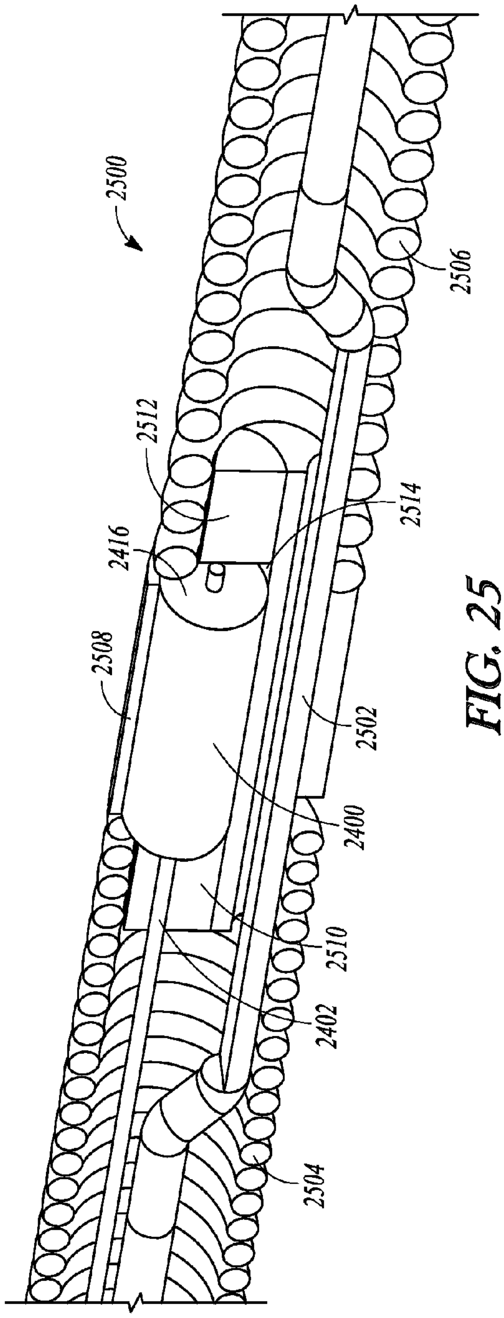

2500
2506
2512
2514
2416
2508
2502
2400
2510
2402
2504

FIG. 25

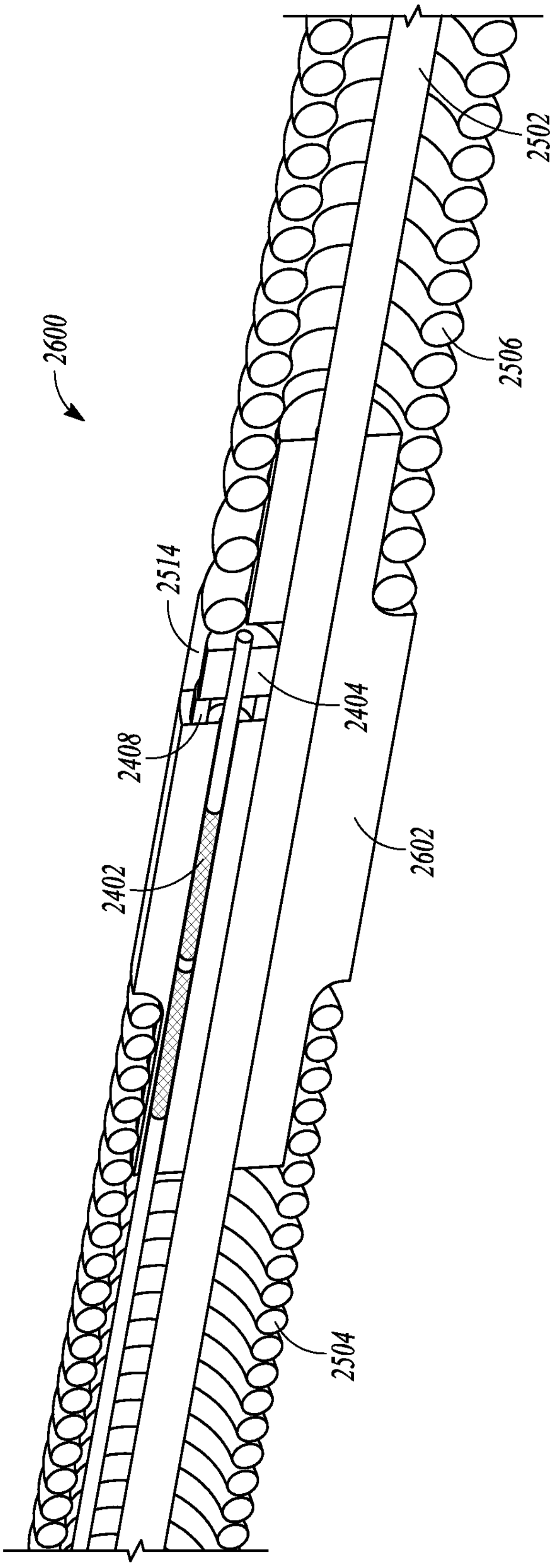


FIG. 26

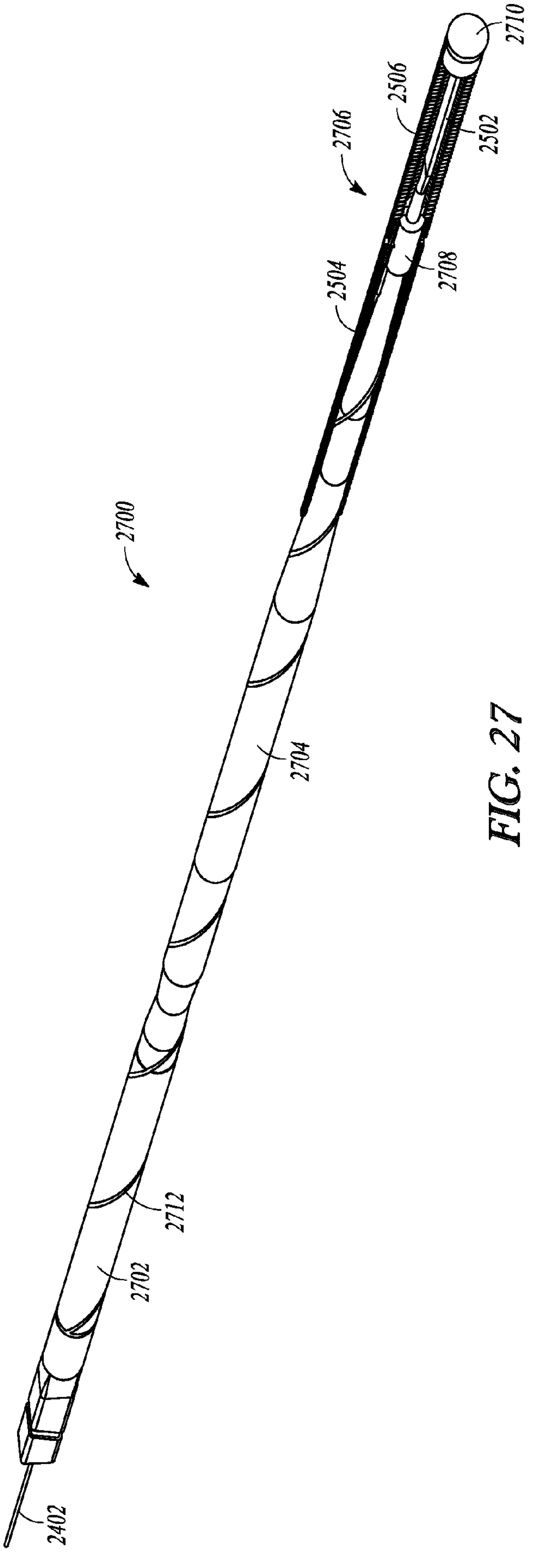


FIG. 27

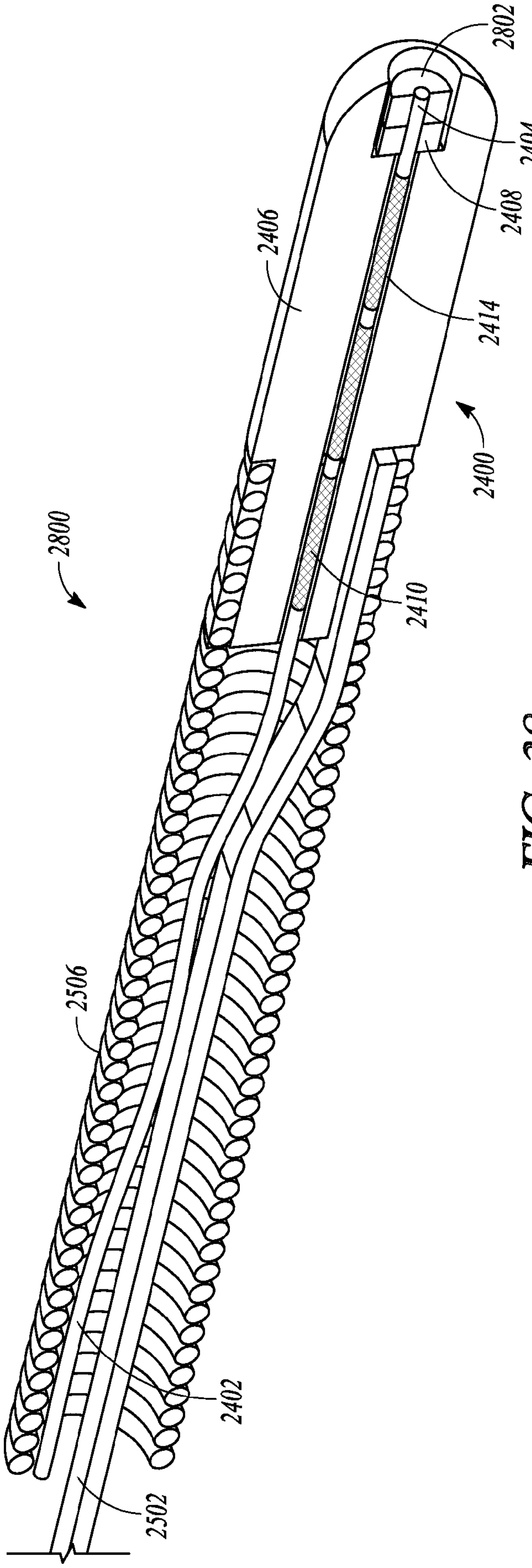


FIG. 28

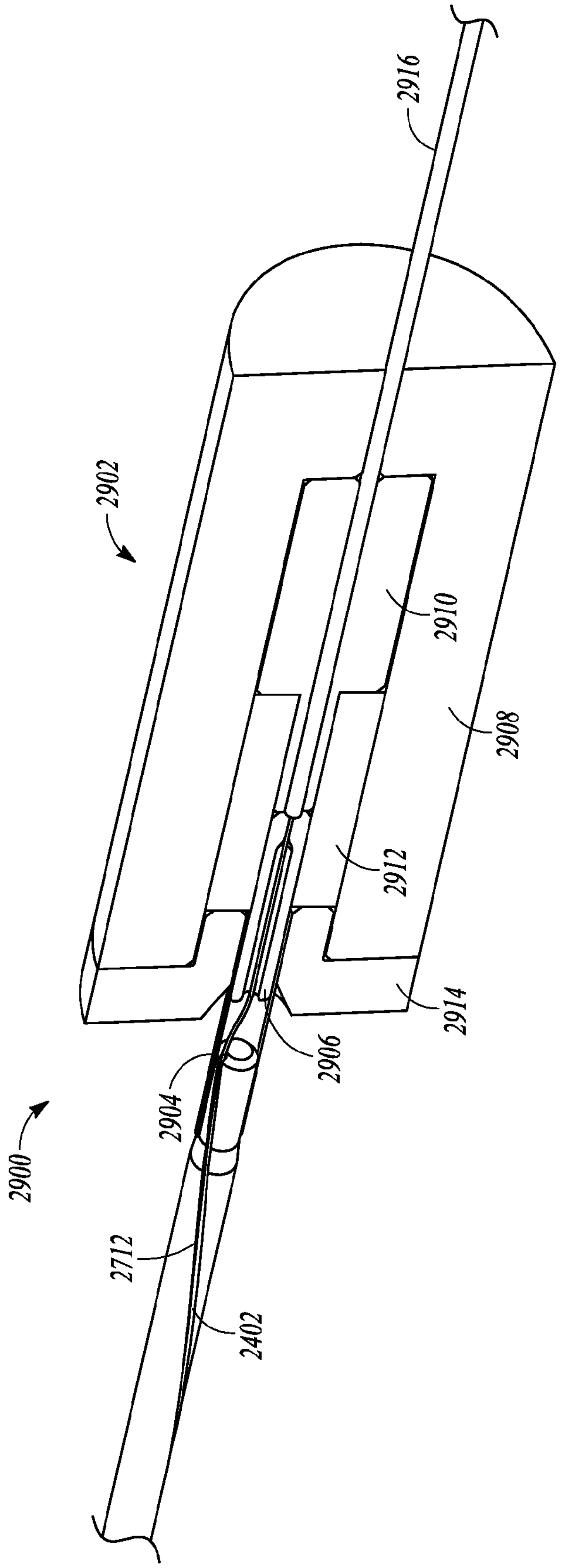


FIG. 29

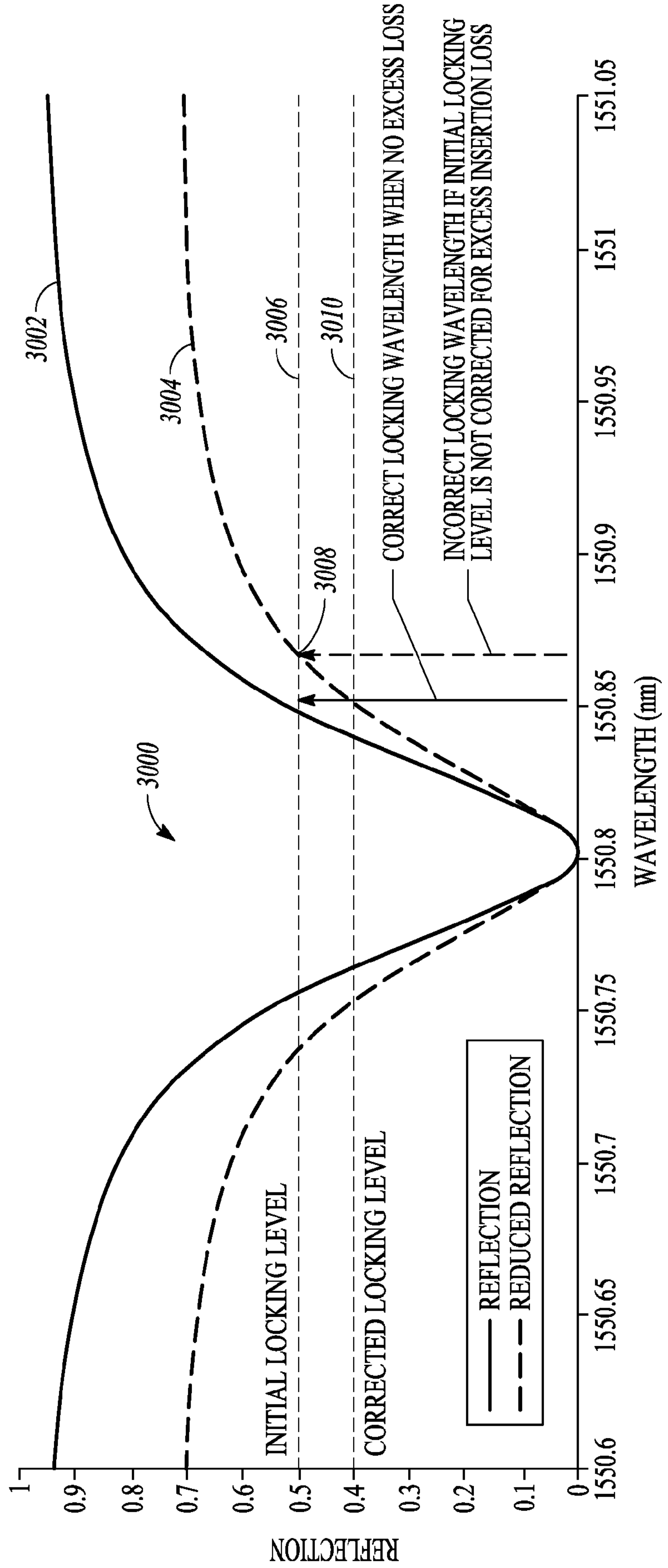

3000
3002
3004
3006
3008
3010
INITIAL LOCKING LEVEL
CORRECTED LOCKING LEVEL
CORRECT LOCKING WAVELENGTH WHEN NO EXCESS LOSS
INCORRECT LOCKING WAVELENGTH IF INITIAL LOCKING LEVEL IS NOT CORRECTED FOR EXCESS INSERTION LOSS
REFLECTION
REDUCED REFLECTION
REFLECTION
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1550.6
1550.65
1550.7
1550.75
1550.8
1550.85
1550.9
1550.95
1551
1551.05
WAVELENGTH (nm)

FIG. 30

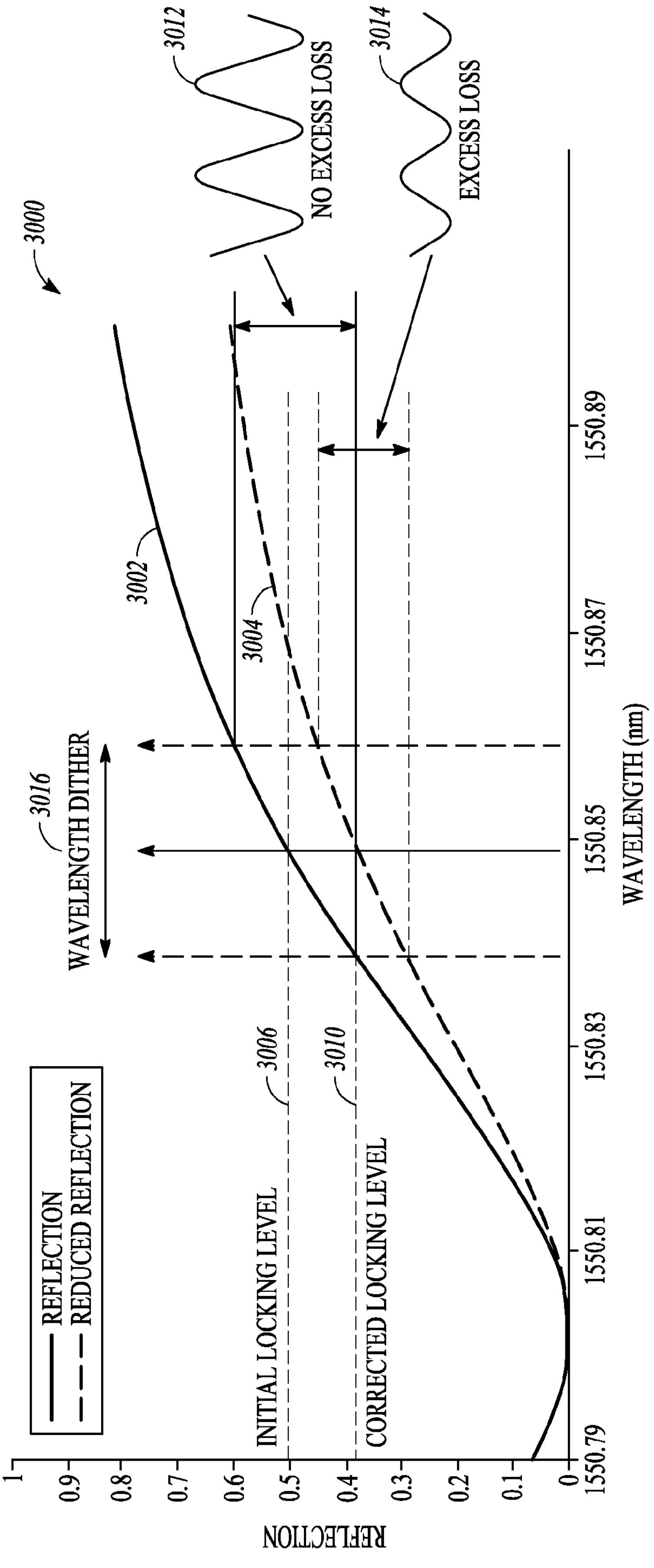

3000
REFLECTION
REDUCED REFLECTION
INITIAL LOCKING LEVEL
CORRECTED LOCKING LEVEL
3006
3010
3016
WAVELENGTH DITHER
3002
3004
3012
NO EXCESS LOSS
3014
EXCESS LOSS
REFLECTION
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1550.79
1550.81
1550.83
1550.85
1550.87
1550.89
WAVELENGTH (nm)

FIG. 31

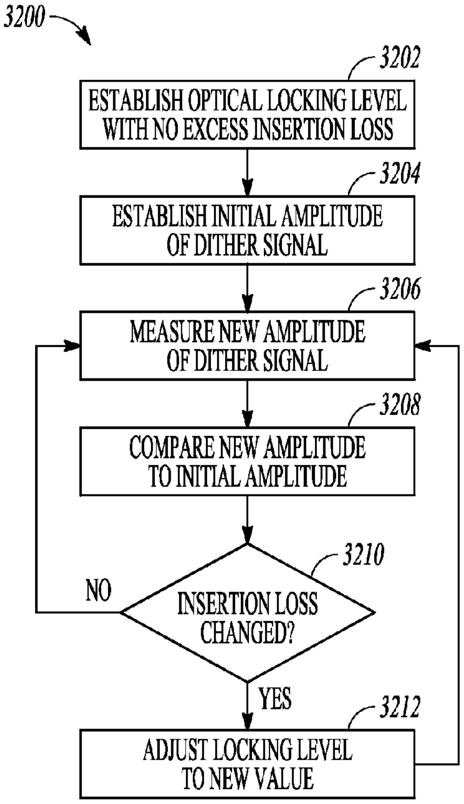

3200
3202
ESTABLISH OPTICAL LOCKING LEVEL WITH NO EXCESS INSERTION LOSS
3204
ESTABLISH INITIAL AMPLITUDE OF DITHER SIGNAL
3206
MEASURE NEW AMPLITUDE OF DITHER SIGNAL
3208
COMPARE NEW AMPLITUDE TO INITIAL AMPLITUDE
3210
INSERTION LOSS CHANGED?
NO
YES
3212
ADJUST LOCKING LEVEL TO NEW VALUE

FIG. 32

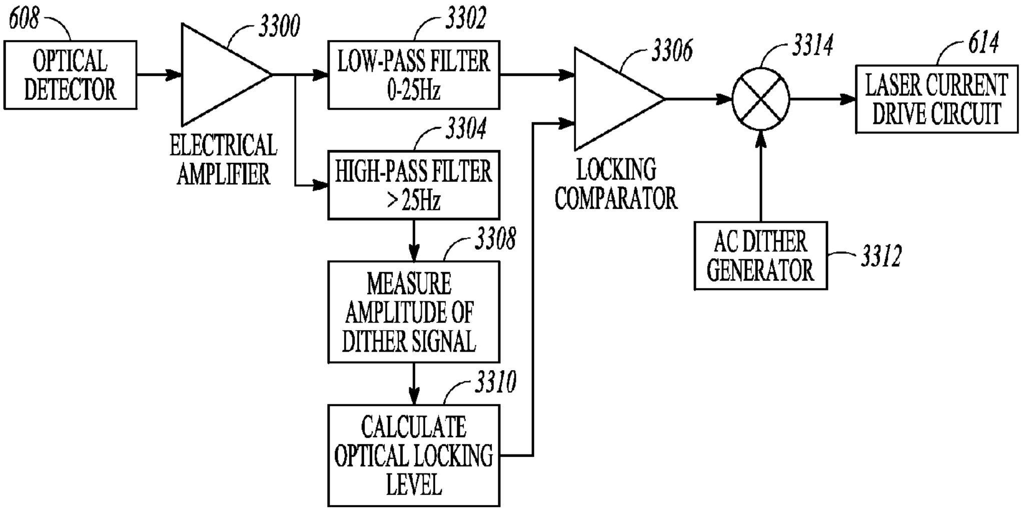

608
OPTICAL DETECTOR
3300
ELECTRICAL AMPLIFIER
3302
LOW-PASS FILTER 0-25Hz
3304
HIGH-PASS FILTER >25Hz
3308
MEASURE AMPLITUDE OF DITHER SIGNAL
3310
CALCULATE OPTICAL LOCKING LEVEL
3306
LOCKING COMPARATOR
3314
AC DITHER GENERATOR
3312
614
LASER CURRENT DRIVE CIRCUIT

FIG. 33

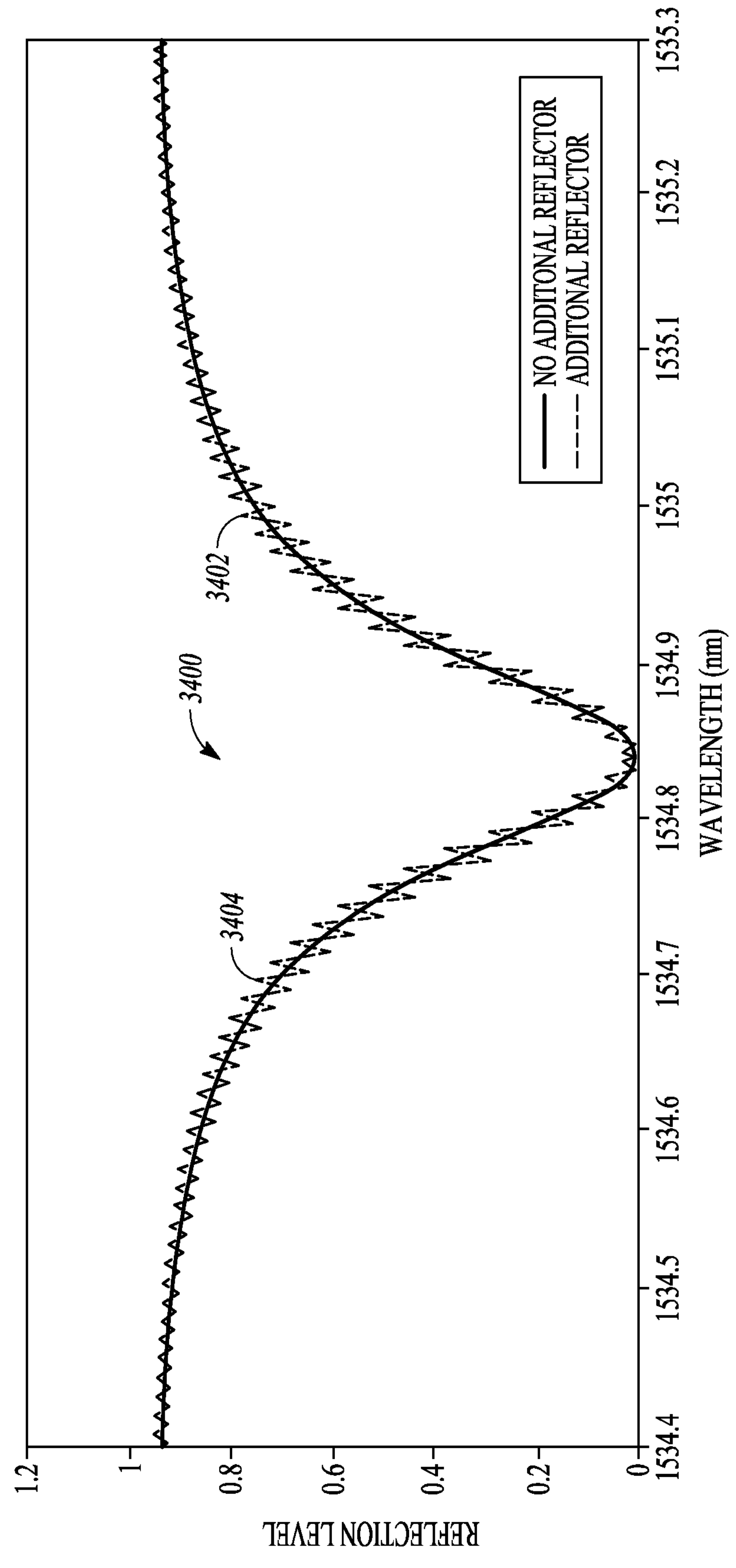

3400
3402
3404
NO ADDITONAL REFLECTOR
ADDITONAL REFLECTOR
REFLECTION LEVEL
1.2
1
0.8
0.6
0.4
0.2
0
WAVELENGTH (nm)
1534.4
1534.5
1534.6
1534.7
1534.8
1534.9
1535
1535.1
1535.2
1535.3

FIG. 34

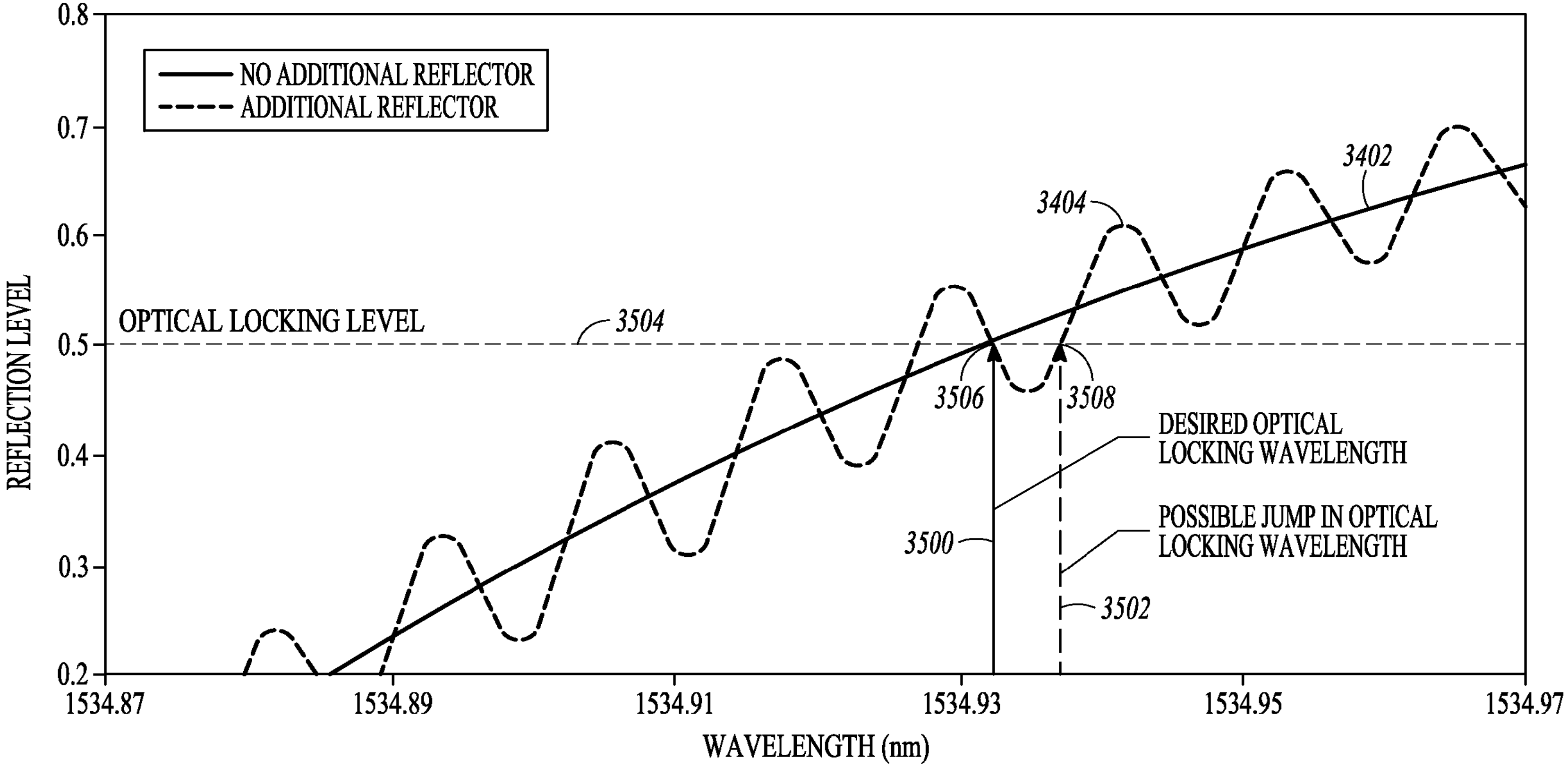

NO ADDITIONAL REFLECTOR
ADDITIONAL REFLECTOR
OPTICAL LOCKING LEVEL
3504
3402
3404
3506
3508
3500
3502
DESIRED OPTICAL LOCKING WAVELENGTH
POSSIBLE JUMP IN OPTICAL LOCKING WAVELENGTH
REFLECTION LEVEL
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1534.87
1534.89
1534.91
1534.93
1534.95
1534.97
WAVELENGTH (nm)

FIG. 35

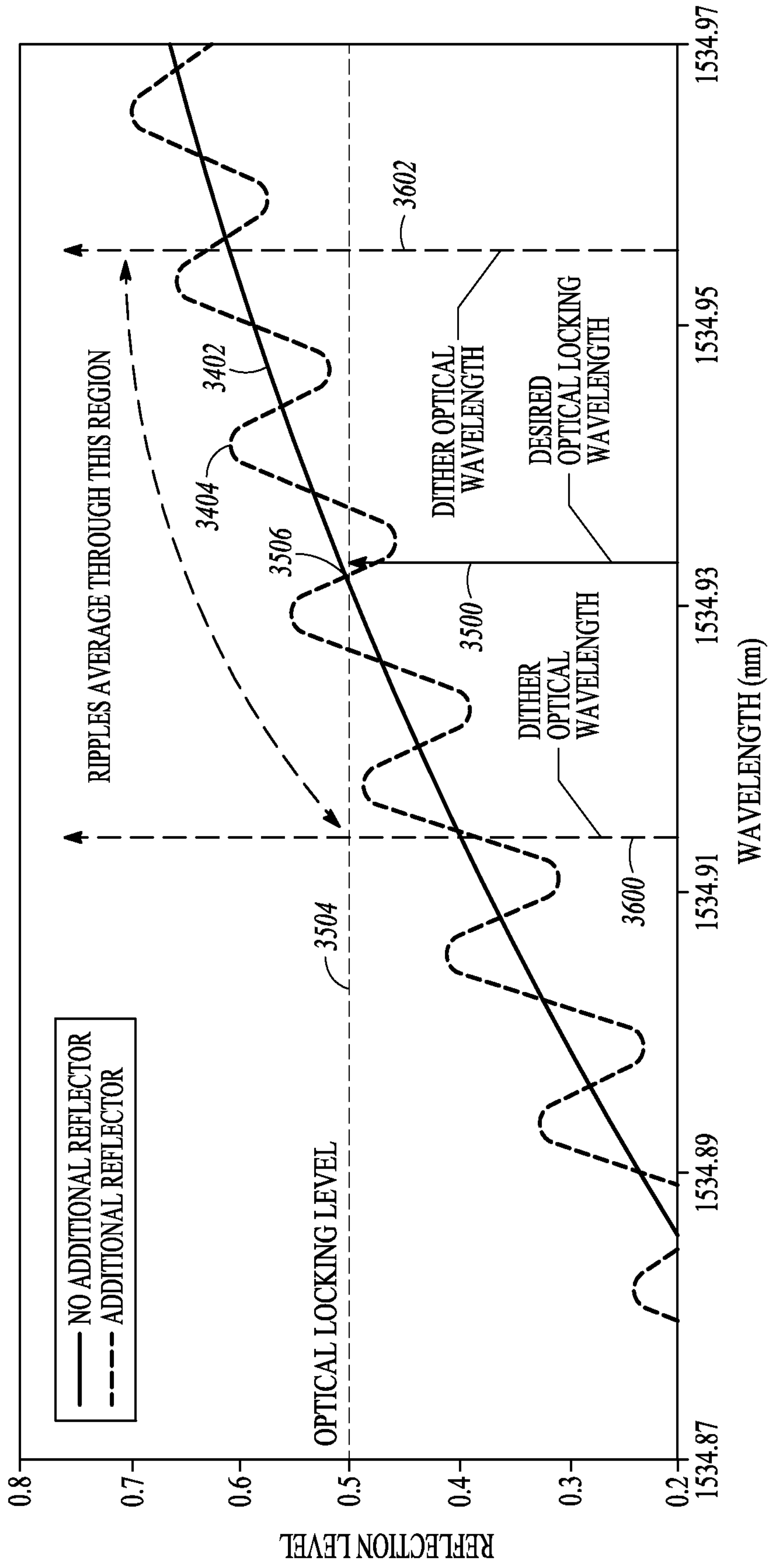

NO ADDITIONAL REFLECTOR
ADDITIONAL REFLECTOR
OPTICAL LOCKING LEVEL
RIPPLES AVERAGE THROUGH THIS REGION
DITHER OPTICAL WAVELENGTH
DESIRED OPTICAL LOCKING WAVELENGTH
DITHER OPTICAL WAVELENGTH
3402
3404
3506
3500
3504
3600
3602
REFLECTION LEVEL
0.8
0.7
0.6
0.5
0.4
0.3
0.2
WAVELENGTH (nm)
1534.87
1534.89
1534.91
1534.93
1534.95
1534.97

FIG. 36

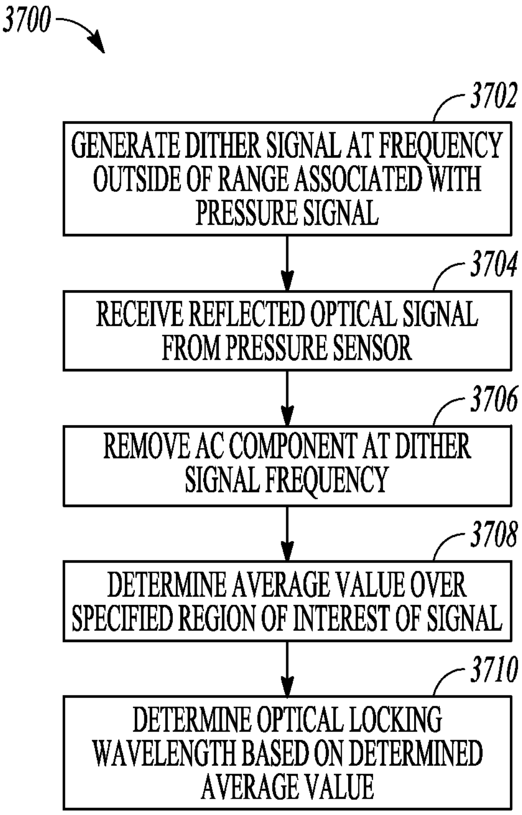

3700
3702
GENERATE DITHER SIGNAL AT FREQUENCY OUTSIDE OF RANGE ASSOCIATED WITH PRESSURE SIGNAL
3704
RECEIVE REFLECTED OPTICAL SIGNAL FROM PRESSURE SENSOR
3706
REMOVE AC COMPONENT AT DITHER SIGNAL FREQUENCY
3708
DETERMINE AVERAGE VALUE OVER SPECIFIED REGION OF INTEREST OF SIGNAL
3710
DETERMINE OPTICAL LOCKING WAVELENGTH BASED ON DETERMINED AVERAGE VALUE

FIG. 37

OPTICAL FIBER PRESSURE SENSOR GUIDEWIRE

[0001] This application is related to (1) U.S. Provisional Application No. 61/791,486 entitled, "OPTICAL FIBER PRESSURE SENSOR GUIDEWIRE" to Eberle et al. and filed on Mar. 15, 2013, and to (2) U.S. Provisional Application No. 61/753,221, entitled, "OPTICAL FIBER PRESSURE SENSOR GUIDEWIRE" to Eberle et al. and filed on Jan. 16, 2013, and to (3) U.S. Provisional Application No. 61/709,781, entitled, "OPTICAL FIBER PRESSURE SENSOR GUIDEWIRE" to Eberle et al. and filed on Oct. 4, 2012, and to (4) U.S. Provisional Application No. 61/659,596, entitled, "OPTICAL FIBER PRESSURE SENSOR GUIDEWIRE" to Eberle et al. and filed on Jun. 14, 2012, and to (5) U.S. Provisional Application No. 61/651,832, entitled, "OPTICAL FIBER PRESSURE SENSOR GUIDEWIRE" to Eberle et al. and filed on May 25, 2012, the entire content of each being incorporated herein by reference in its entirety, and the benefit of priority of each is claimed herein.

TECHNICAL FIELD

[0002] This document pertains generally to pressure sensing devices and methods and, in particular, to pressure sensing devices and methods using optical elements and techniques.

BACKGROUND

[0003] U.S. Patent Application Publication No. 2009/0180730 to Foster et al. is directed toward a device for sensing an acoustic signal. The device includes a flexible portion including a laser active region having an emitted wavelength that varies according to a mechanical force acting on the flexible portion, and including a flexible support member operable to flex or bend according to the acoustic signal. The flexible portion is coupled with the support member so as to cause the flexible portion to flex or bend in accordance with the support member, thereby changing the emitted wavelength of the laser active region of the flexible portion.

[0004] U.S. Pat. No. 7,680,363 to Wakahara et al. ("Wakahara") is directed toward an optical fiber pressure sensor capable of detecting a more minute pressure change. A base film is formed with a through hole passing through first and second surfaces. An optical fiber is fixed to the base film at a region other than the Fiber Bragg Grating (FBG) portion, such that the FBG portion is positioned on the through hole in plan view. The optical fiber pressure sensor is attached to an object body such that the second surface of the base film is closely attached to a surface of the object body directly or indirectly.

OVERVIEW

[0005] The present applicant has recognized, among other things, that other approaches to pressure sensing guidewires exhibit mechanical performance suitable for diagnostic assessment of coronary obstructions, but typically are not suitable for delivery of therapeutic devices. The present applicant has recognized that the other pressure sensing technology, namely piezoresistive or piezocapacitive silicon pressure sensors, and associated electrical cables, are relatively large compared to the size of the components of a typical therapy delivering guidewire. The present applicant has recognized that the incorporation of such other pressure sensing technology into a coronary guidewire substantially restricts the design of the mechanical components of the guidewire and results in significant compromises to the mechanical performance. The present applicant has recognized that a smaller pressure sensing technology, when incorporated into a contemporary coronary guidewire, would be advantageous in restoring the required mechanical performance requirements.

[0006] Optical fiber technology can be used in pressure sensors for oil discovery and production, as well as in larger diagnostic catheters for patients. The present applicant has recognized that telecommunication industry standard optical fiber would be too large to incorporate into high performance coronary guidewires. Accordingly, the present applicant has recognized, among other things, that miniaturization of the optical fiber and optical fiber based pressure sensor presents both a major challenge and a major advantage for incorporation into a coronary guidewire while minimizing the impact on the mechanical performance of the guidewire.

[0007] The present applicant has recognized, among other things, that the intrinsic sensitivity of an optical fiber sized for insertion into a body lumen may not be sufficient to generate an easily detectable signal within the range of pressures associated with a patient. The present applicant has recognized that miniaturization of the optical fiber can impart more flexibility into the fiber. This can be used to mechanically enhance the sensitivity of the fiber to pressure, such as with an extrinsic arrangement. The present applicant has recognized that using Fiber Bragg Gratings in the miniaturized optical fiber can provide a highly cost effective and readily manufacturable design. In addition, the present applicant has recognized that one or more other factors—such as the temperature coefficient of one or more Fiber Bragg Gratings (FBGs)—can be significantly higher than the intrinsic pressure sensitivity of the optical fiber. As such, a small drift in temperature within a patient can appear as a large pressure change artifact, which, in the context of pressure sensing, is unwanted and likely not acceptable due to the need for accurate pressure measurements. Accordingly, the present applicant has recognized, among other things, that it can be advantageous to provide an optical fiber pressure sensor guidewire that can include temperature calibration, compensation, or correction for an optical fiber pressure sensor, such as a Fiber Bragg Grating (FBG) arrangement for sensing pressure within a body lumen.

[0008] In one example, the disclosure is directed to an apparatus for insertion into a body lumen. The apparatus comprises an optical fiber pressure sensor comprising an optical fiber configured to transmit an optical sensing signal, an ambient temperature compensated Fiber Bragg Grating (FBG) interferometer in optical communication with the optical fiber, the FBG interferometer configured to receive a pressure and modulate, in response to the received pressure, the optical sensing signal, and a sensor membrane in physical communication with the FBG interferometer, the membrane configured to transmit the received pressure to the FBG interferometer.

[0009] This overview is intended to provide an overview of subject matter of the present patent application. It is not intended to provide an exclusive or exhaustive explanation of the invention. The detailed description is included to provide further information about the present patent application.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] In the drawings, which are not necessarily drawn to scale, like numerals may describe similar components in different views. Like numerals having different letter suffixes may represent different instances of similar components. The drawings illustrate generally, by way of example, but not by way of limitation, various embodiments discussed in the present document.

[0011] FIG. **1** is a cross-sectional side view illustrating generally, by way of example, but not by way of limitation, an example of an FBG pressure sensor in an optical fiber.

[0012] FIG. **2** is a cross-sectional side view illustrating generally, by way of example, but not by way of limitation, an example of an FBG grating interferometer sensor.

[0013] FIG. **3** is a conceptual diagram illustrating various example configurations FBG of an optical fiber pressure sensor, in accordance with this disclosure.

[0014] FIGS. **4**A-**4**C depict various conceptual response diagrams related to the conceptual diagram of FIG. **3**.

[0015] FIG. **5** is a block diagram of an example of an ambient temperature compensation technique in accordance with this disclosure.

[0016] FIG. **6**A is a block diagram of an example of a laser tracking system, in accordance with this disclosure.

[0017] FIG. **6**B is a block diagram of an example of a temperature compensation technique in accordance with this disclosure.

[0018] FIGS. **7**A-**7**C depict an example of a pressure sensor that can be used to implement various techniques of this disclosure.

[0019] FIGS. **8**A-**8**C depict another example of a pressure sensor that can be used to implement various techniques of this disclosure.

[0020] FIGS. **9**A-**9**C depict another example of a pressure sensor that can be used to implement various techniques of this disclosure.

[0021] FIGS. **10**A-**10**D depict another example of a pressure sensor that can be used to implement various techniques of this disclosure.

[0022] FIG. **11** depicts a conceptual response diagram related to the example of a pressure sensor shown in FIG. **10**D.

[0023] FIGS. **12**A-**12**C depict another example of a pressure sensor that can be used to implement various techniques of this disclosure.

[0024] FIGS. **13**A-**13**C depict an example of a guidewire in combination with an optical fiber pressure sensor, in accordance with this disclosure.

[0025] FIGS. **14**A-**14**C depict another example of a guidewire in combination with an optical fiber pressure sensor, in accordance with this disclosure.

[0026] FIGS. **15**A-**15**C depict another example of a guidewire in combination with an optical fiber pressure sensor, in accordance with this disclosure.

[0027] FIG. **16** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure.

[0028] FIG. **17** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure.

[0029] FIG. **18** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure.

[0030] FIG. **19** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure.

[0031] FIG. **20** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure.

[0032] FIGS. **21**A-**21**D depict another example of a guidewire in combination with an optical fiber pressure sensor, in accordance with this disclosure.

[0033] FIG. **22** depicts an example of a combination of a guidewire with an optical fiber pressure sensor and an imaging sensor, in accordance with this disclosure.

[0034] FIGS. **23**A-**23**B depict another example of a guidewire in combination with an optical fiber pressure sensor, in accordance with this disclosure.

[0035] FIG. **24** shows an example of a portion of a concentric pressure sensor assembly.

[0036] FIG. **25** shows an example of the pressure sensor assembly as it can be prefinished and included or otherwise incorporated into a percutaneous intravascular guidewire assembly.

[0037] FIG. **26** shows an example illustrating how components of the pressure sensor assembly can be integrated into or otherwise incorporated into a percutaneous intravascular guidewire assembly.

[0038] FIG. **27** shows an example in which components of the pressure sensing assembly can be retrofitted to or otherwise integrated into an existing guidewire assembly.

[0039] FIG. **28** shows an example in which the pressure sensor assembly (e.g., as explained herein) can be located at a distal end of a guidewire assembly.

[0040] FIG. **29** shows an example of a proximal region of a guidewire assembly, such as one of the various guidewire assemblies described herein, terminating at a proximal end connector.

[0041] FIG. **30** depicts a conceptual response diagram illustrating the effect of an uncorrected locking level on a locking wavelength.

[0042] FIG. **31** depicts the conceptual response diagram of FIG. **30** compensated for optical insertion loss in an optical pressure sensor using various techniques of this disclosure.

[0043] FIG. **32** is a flow diagram illustrating an example of a method for compensating for optical insertion loss in an optical pressure sensor using various techniques of this disclosure.

[0044] FIG. **33** is a block diagram of an example of a portion of the laser tracking system of FIG. **6**A for compensating for optical insertion loss in an optical pressure sensor using various techniques of this disclosure, in accordance with this disclosure.

[0045] FIG. **34** depicts a conceptual response diagram illustrating undesirable optical resonances caused by additional reflection in an optical system.

[0046] FIG. **35** depicts the conceptual response diagram of FIG. **34** further illustrating undesirable locking circuit wavelength hopping.

[0047] FIG. **36** depicts the conceptual response diagram of FIG. **35** compensated for optical cavity noise using various techniques of this disclosure.

[0048] FIG. **37** depicts a flow diagram illustrating an example of a method for compensating for optical cavity noise in an optical pressure sensor using various techniques of this disclosure.

DETAILED DESCRIPTION

[0049] Before or during an invasive medical procedure, it can be desirable for a clinician, e.g., a physician, to take one or more pressure measurements from within a body lumen of a patient, e.g., a blood vessel, such as an artery or vein. For example, before implanting a stent at the site of an occlusion in a blood vessel, it can be desirable to determine the physiologic effect of the occlusion on the patient before making a decision whether to implant the stent. One way to determine the effect of the occlusion on the patient is to measure the drop in blood pressure across the occlusion, such as using a Fractional Flow Reserve (FFR) technique. Generally speaking, if there is more than a 20% drop in pressure across the occlusion during maximum blood flow, the patient can be considered a candidate for stent implantation. Otherwise, it can be preferable to treat the patient with a pharmaceutical regimen rather than implant a stent. Occlusions that look visibly similar, using an intravascular or other imaging modality, can be vastly different in terms of pressure drop across the occlusion. Therefore, an accurate measurement of pressure drop across an occlusion may help to tease out those occlusions that should be treated using a stent from those occlusions that are adequately treated by a pharmaceutical regimen.

[0050] As mentioned above, the present applicant has recognized, among other things, the advantages and desirability of miniaturization of an optical fiber and optical fiber based pressure sensor for incorporation into a coronary guidewire, which, in turn, can optionally be used for guiding a balloon catheter or other device for positioning and securing the stent at the desired location. An optical fiber pressure sensor based on FBG technology can have an intrinsic pressure sensitivity of about 0.00038 picometers (pm)/mmHg (about 0.02 pm/psi). Such an optical fiber pressure sensor based on FBG technology can have an intrinsic temperature sensitivity of about 10 pm/degree Celsius (° C.). The temperature sensitivity can increase if the optical fiber pressure sensor includes or is integrated or packaged with one or more materials having a higher coefficient of thermal expansion. The range of blood pressures in a patient is relatively low, e.g., about 0 millimeters of mercury (mmHg) to about 300 mmHg, and there is a need for high resolution within that range, e.g., 1-2 mmHg, where 51.7 mmHg equals 1 pound per square inch (psi), such as to adequately characterize the blood pressure drop across a blood vessel occlusion.

[0051] Based on these numbers, an uncompensated or uncorrected change in temperature of 0.1° C. can result in an equivalent intrinsic pressure drift of about 2632 mmHg or more than 1000 times the desired blood pressure measurement resolution. As mentioned above, when using an optical fiber pressure sensor capable of insertion into a body lumen of a patient, e.g., an animal such as a human, a small, uncompensated or uncorrected drift in temperature within the patient, e.g., as a result of an injected imaging contrast medium, can appear as an artifact that incorrectly indicates a large change in pressure. This can be due in part to the relatively low intrinsic sensitivity of the optical fiber pressure sensor to pressure and the relatively high intrinsic sensitivity to temperature of the optical fiber associated with the optical fiber pressure sensor. As such, a small, uncompensated drift in temperature can be unacceptable due to the need for accurate pressure measurements.

[0052] Using one or more techniques of this disclosure, a Fiber Bragg Grating (FBG) interferometer or other optical fiber pressure sensor guidewire can be temperature compensated, such as for permitting accurate pressure sensing within a body lumen. In addition, this disclosure describes techniques for increasing the overall sensitivity of an optical fiber pressure sensor guidewire, such as to generate an easily detectable blood pressure indicating output signal providing the desired resolution and accommodating the range of pressures associated with the patient.

[0053] It should be noted that the optical fiber described in this disclosure can have a diameter of between about 25 microns and about 30 microns. By way of comparison, a standard telecommunication optical fiber has a diameter of about 125 microns. This marked reduction in size can cause numerous challenges arising from the differences in the optics properties of such a drastically reduced size optical fiber.

[0054] FIG. **1** is a cross-sectional side view illustrating generally, by way of example, but not by way of limitation, an example of a strain-detecting or pressure-detecting optical FBG sensor **100** in an optical fiber **105**. The FBG sensor **100** can sense pressure received from a nearby area, and can transduce the received pressure into an optical signal within the optical fiber **105**. The FBG sensor **100** can include Fiber Bragg gratings **110**A-B in an optical fiber core **115**, such as surrounded by an optical fiber cladding **120**. The gratings **110**A-B can be separated by a strain or pressure sensing region **125**, which, in an example, can be about a millimeter in length. In an example, strain or pressure can be sensed, such as by detecting a variation in length of the optical path between these gratings **110**A-B.

[0055] A Fiber Bragg Grating can be implemented as a periodic change in the optical refractive index of a selected axial portion of the optical fiber core **115**. Light of specific wavelengths traveling down such a portion of the core **115** will be reflected. The period (distance or spacing) **130** of the periodic change in the optical index can determine the particular wavelengths of light that will be reflected. The degree of optical refractive index change and the axial length **135** of the grating **110**A-B can determine the ratio of light reflected to that transmitted through the grating **110**A-B.

[0056] FIG. **2** is a cross-sectional side view illustrating generally, by way of example, but not by way of limitation, an operative example of an interferometric FBG sensor **100**. The example of FIG. **2** can include two gratings **110**A-B, which can act as mirrors that can both be partially reflective such as for a specific range of wavelengths of light passing through the fiber core **115**. Generally, the reflectivity of each grating of a particular pair of gratings **110**A-B will be substantially similar to the other grating in that particular pair of gratings **110**A-B, but can differ between gratings of a particular pair of gratings **110**A-B for particular implementations, or between different pairs of gratings **110**A-B, or both. This interferometric arrangement of FBGs **110**A-B can be capable of discerning the "optical distance or optical pathlength" between FBGs **110**A-B with extreme sensitivity. The "optical distance or pathlength" can be a function of the effective refractive index of the material of fiber core **115** as well as the physical distance **125** between FBGs **110**A-B. Thus, a change in the refractive index can induce a change in optical path length, even though the physical distance **125** between FBGs **110**A-B has not substantially changed.

[0057] An interferometer, such as can be provided by the FBG sensor **100**, can be understood as a device that can measure the interference between light reflected from each of the partially reflective FBGs **110**A-B. When the optical path length between the FBG gratings **110**A-B is an exact integer multiple of the wavelength of the optical signal in the optical fiber core **115**, then the light that passes through the FBG sensor **100** will be a maximum and the light reflected will be a minimum, such that the optical signal can be substantially fully transmitted through the FBG sensor **100**. This addition or subtraction of grating-reflected light, with light being transmitted through the optical fiber core **115**, can be conceptualized as interference. The occurrence of full transmission or minimum reflection can be called a "null" and can occur at a precise wavelength of light for a given optical path length. Measuring the wavelength at which this null occurs can yield an indication of the length of the optical path between the two partially reflective FBGs **110**A-B. In such a manner, an interferometer, such as can be provided by the FBG optical fiber pressure sensor **100**, can sense a small change in distance, such as a change in the optical distance **125** between FBGs **110**A-B resulting from a received change in pressure. In this manner, one or more FBG sensors can be used to sense one or more pressures within a body lumen of a patient. This arrangement is an example of an FBG Fabry-Perot interferometer, which can be more particularly described as an Etalon, because the physical distance **125** between the FBGs **110**A-B is substantially fixed.

[0058] The sensitivity of an interferometer, such as can be included in the FBG sensor **100**, can depend in part on the steepness of the "skirt" of the null in the frequency response. The steepness of the skirt can be increased by increasing the reflectivity of the FBGs **110**A-B, which also increases the "finesse" of the interferometer. Finesse can refer to a ratio of the spacing of the features of an interferometer to the width of those features. To provide more sensitivity, the finesse can be increased. The higher the finesse, the more resonant the cavity, e.g., two FBGs and the spacing therebetween. The present applicant has recognized, among other things, that increasing the finesse or steepness of the skirt of FBG sensor **100** can increase the sensitivity of the FBG sensor **100** to pressure within a particular wavelength range but can decrease the dynamic range of the FBG sensor **100**. As such, keeping the wavelength of the optical sensing signal within the wavelength dynamic range of the FBG sensor **100** can be advantageous, such as to provide increased sensitivity to pressure. In an example, a closed-loop system can monitor a representative wavelength (e.g., the center wavelength of the skirt of the filtering FBG sensor **100**). In response to such information, the closed-loop system can adjust the wavelength of an optical output laser to remain substantially close to the center of the skirt of the filter characteristic of the FBG sensor **100**, even as forces external to the optical fiber **105**, such as bending and stress, can cause shifting of the center wavelength of the skirt of the filter characteristic of the FBG sensor **100**.

[0059] In an example, such as illustrated in FIG. **2**, the interferometric FBG sensor **100** can cause interference between that portion of the optical beam that is reflected off the first partially reflective FBG **110**A with that reflected from the second partially reflective FBG **110**B. The wavelength of light where an interferometric null will occur can be very sensitive to the "optical distance" between the two FBGs **110**A-B. The interferometric FBG sensor **100** of FIG. **2** can provide another very practical advantage. In the example illustrated in FIG. **2**, the two optical paths along the fiber core **115** are the same, except for the sensing region between FBGs **110**A-B. This shared optical path can ensure that any optical changes in the shared portion of optical fiber **105** will have substantially no effect upon the interferometric signal; only the change in the sensing region **125** between FBGs **110**A-**110**B is sensed. Additional information regarding FBG strain sensors can be found in U.S. Patent Application Publication No. 2010/0087732 to Eberle et al., which is incorporated herein by reference in its entirety, including its disclosure of FBGs and their applications.

[0060] FIG. **3** is a conceptual diagram illustrating various examples of FBG configurations of an FBG optical fiber pressure sensor **300**, in accordance with this disclosure. The FBG optical fiber pressure sensor **300** can include an optical fiber **302** that can extend longitudinally through a stiff, rigid, or solid mounting **304**. As seen in FIG. **3**, a portion of the optical fiber **302** extends beyond a distal end **306** of the mounting **304**. The optical fiber **302** and the mounting **304** can be disposed within a housing **308**. Using one or more techniques of this disclosure, such as shown and described in detail in this disclosure with respect to FIGS. **13-15**, an optical fiber pressure sensor can include an optical fiber that can be combined with a guidewire, such as for diagnostic assessment of a coronary obstruction, for example.

[0061] As described in more detail below, two or more FBGs, e.g., FBGs **1-4**, can be included in the FBG pressure sensor **300**, such as for pressure sensing. One or more additional gratings can be included, and such additional one or more gratings can be insulated or isolated from influence caused by (1) bending (of the fiber) and/or (2) pressure. These insulated or isolated additional gratings can be arranged for providing one or more of temperature calibration, compensation, or correction. In an example, the additional grating(s) can provide an independent (of pressure and fiber bending) measure of temperature, such as for feedback to a temperature compensation scheme or method of an optical fiber pressure sensor **300**. The optical fiber pressure sensor **300** can optionally include a sealed or other cavity (not depicted in FIG. **3**), such as below a portion of the optical fiber **302**, e.g., below FBG **3**, which can amplify changes in pressure, or otherwise provide increased optical response to changes in pressure. Some example configurations that can include a sealed cavity are described in more detail below.

[0062] In FIG. **3**, FBG **1** can be a FBG that produces a broad reflection band at the center of the spectrum of FBG **1**, such as shown generally at **400** in the response diagram depicted in FIG. **4**A, in which the x-axis represents wavelength and the y-axis represents the intensity of the reflected light. FBG **2** and FBG **3**, although depicted and referred to as separate gratings, can represent a single FBG that can be split into two identical, smaller FBGs and separated by a small phase difference (or phase-shifted) of 180 degrees, for example.

[0063] For example, the phase shift could be built into a phase mask that is used to write the gratings onto the fiber, e.g., an electron beam generated phase mask. Illumination of the phase mask can result in a phase shift. In another example, a first grating can be written onto the fiber via a phase mask. Then, the phase mask can be moved by a distance equivalent to a 180 degree phase shift, for example, and a second grating can be written onto the fiber.

[0064] The reflections from FBG **2** interfere with the reflections from FBG **3** because of the phase shift between FBG **2** and FBG **3**, shown as a phase shift region **312**A in FIG. **3**. As a result, a narrow transmission notch **402** is created within the reflection band shown generally at **404** in the wavelength response diagram depicted in FIG. **4**A.

[0065] In an example, pressure changes can be detected by the optical fiber pressure sensor **300**, e.g., within a patient's body, such as by detecting or amplifying the phase-shift between two FBGs, e.g., FBG **2** and FBG **3**. This technique is in contrast to optical pressure sensing techniques that measure the shift in wavelength of the FBG itself. Using various techniques of this disclosure, the phase-shift between FBGs can be modified rather than a wavelength shift of the FBG itself.

[0066] As seen in FIG. **3**, FBG **3** can extend distally outward beyond the distal end **306** of the mounting **304**. A change in pressure can cause the distal portion **310** of the optical fiber **302** to bend slightly against the distal end **306** of the mounting **304**, which, in turn, can cause the distal end **306** to mechanically act upon the phase-shift region **312**A between FBG **2** and FBG **3**. The mechanical forces acting upon the phase-shift region **312**A between FBG **2** and FBG **3** can concentrate a stress in the phase-shift region **312**A of the optical fiber **302**. The concentrated stress in the phase-shift region **312**A changes the refractive index of the optical fiber **302** in the stressed region, which, in turn, can alter, or amplify, the phase relationship between FBG **2** and FBG **3**. The change in phase-shift between FBG **2** and FBG **3** can be quantified and the change in pressure can be determined from the quantified phase-shift.

[0067] For example, as described in more detail below, a wavelength of a narrow band laser (in relation to the wavelength response of FBGs **2** and **3**) can be locked on a point on a slope **406** of the narrow transmission notch **402** in FIG. **4**A, e.g., at about 50% of the depth of the notch **402**. As the pressure changes, the notch **402** shifts and, consequently, the point on the slope **406** shifts. A tracking circuit can then track the point on the slope **406**, and a phase-shift can be determined from its change in position. The intensity of reflected light will be modified when the notch **402** moves. In the example in the diagram, if the notch **402** moves downward in wavelength, then the intensity of the signal reflected will increase. If the notch **402** moves upward in wavelength, then the intensity of the signal reflected will decrease. If it is chosen that the laser wavelength would be on the opposite side of the notch **402**, then the effect would be reversed.

[0068] As indicated above, one or more external factors such as the temperature coefficient of one or more Fiber Bragg Gratings (FBGs) can be significantly higher than the intrinsic pressure sensitivity of the optical fiber pressure sensor that can include such FBGs. As such, a small drift in temperature within a patient can spuriously appear as a large change in pressure. Such a temperature-induced artifact in the pressure response signal may be unacceptable due to the need for accurate pressure measurements. The present applicant has recognized, among other things, that it can be advantageous to provide the optical fiber pressure sensor guidewire of this disclosure with a temperature compensated Fiber Bragg Grating (FBG) arrangement, such as for accurately sensing pressure within a body lumen, for example.

[0069] The conceptual diagram of FIG. **3** can be used to describe several different configurations for a temperature compensated FBG optical fiber pressure sensor **300**. Examples of more detailed configurations are shown and described below with respect to FIGS. **7-10** and FIG. **12**.

[0070] In a first example of a configuration, a FBG optical fiber pressure sensor **300** can include FBGs **1-3** (FBG **4** need not be included). FBGs **2** and **3**, which can be configured to operate at the same wavelength (e.g., a first wavelength between about 1000 nanometers (nm) and about 1700 nm), can form a phase-shift structure that can be used to sense pressure, such as described in detail above. To recap, a concentration in stress in the phase-shift region between the two gratings (e.g., FBG **2** and FBG **3**), as a result of the bending of the optical fiber **302** changes the refractive index of the optical fiber **302** in the phase-shift region. The change in the refractive index of the optical fiber **302** in the phase-shift region can alter the phase relationship between FBG **2** and FBG **3**, which can be quantified, and the change in pressure can be determined from the quantified phase-shift. The phase-shift, however, is not compensated for temperature, which may not acceptable, as explained above.

[0071] FBG **1** can be configured to be substantially independent of pressure, such as by locating it within the stiff, rigid, or solid mounting **308**. Therefore, FBG **1** can be used to measure ambient temperature, such as to provide a temperature compensated optical fiber pressure sensor. FBG **1** can be configured to operate at a substantially different wavelength than that of FBGs **2** and **3** (e.g., a second wavelength between 1000 nanometers (nm) and 1700 nm). In this manner, FBG **1** has no interaction with FBGs **2** and **3**. As such, FBG **1** can provide a measure of ambient temperature that is independent of pressure variations. In a manner similar to that described above with respect to tracking the change in position of the notch **402** of FIG. **4**A, a wavelength of a narrow band laser (in relation to the response of the FBG **1**) can be locked on a point on a slope **408** of the response of FBG **1** in FIG. **4**A, e.g., at about 50% of the depth of the response. The wavelength of the locked point on the slope **408** shifts as the temperature changes. A tracking circuit can then track the locked point on the slope **408** and a change in ambient temperature can be determined from its change in position.

[0072] In order to generate a pressure signal that is ambient temperature compensated, the signal generated by FBG **1** can be used as a reference to null a shift in temperature. A controller circuit can be configured to control subtraction of the temperature reference signal (from FBG **1**) from the temperature and pressure signal (from FBGs **2** and **3**), such as to generate a temperature compensated pressure signal. An example of a temperature compensation technique is described in more detail in this disclosure, such as with respect to FIG. **5**.

[0073] In a second example of a configuration, the FBG sensor **300** can include an optical fiber, a stiff, rigid, or solid mounting, a housing, and FBGs **1-3** (FBG **4** need not be included). FBGs **1-3** can be positioned very close to each other and can thus form a very compact structure. FBGs **2** and **3**, which can be configured to operate at the same wavelength (e.g., a first wavelength between 1000 nm and 1700 nm), can form a phase-shift structure that can be used to sense pressure. The phase shift between FBGs **2** and **3** can result in a signal that changes with pressure and temperature.

[0074] FBG **1** can be configured to operate at a similar, but slightly different, wavelength than that of FBGs **2** and **3** (e.g., a second wavelength near the first wavelength of FBGs **2** and **3** and between 1000 nm and 1700 nm). In this manner, FBG **1** can form a resonant feature with FBGs **2** and **3** at a slightly different wavelength. FBG **1** can result in a signal that changes with respect to temperature changes.

[0075] A conceptual illustration of the response of FBGs **1-3** is depicted in FIG. **4**B, where the x-axis represents wavelength and the y-axis represents the intensity of the reflected light. Again, the techniques of this disclosure need not sense a shift in the wavelength of the gratings, but can instead sense a change in the phase between the gratings. The temperature compensating element, e.g., FBG **1**, is in resonance with part of the pressure sensing structure, e.g., FBGs **2** and **3**. As such, FBG **1** can be linked to the pressure sensing structure rather than being an independent element. Such a configuration can provide a compact structure.

[0076] Similar to the first example of a configuration, such as to generate a pressure signal that is temperature compensated, the signal generated by FBG **1** can be used as a reference, such as to null a shift in temperature. A slope **410** of the notch **412** and a slope **414** of the notch **416** can each be tracked and used to determine changes in temperature and pressure, such as based on their respective changes in position. A controller circuit can be configured to control the subtraction of the temperature reference signal (e.g., from FBG **1**) from the temperature and pressure signal (e.g., from FBGs **2** and **3**) such as to generate a temperature compensated pressure signal.

[0077] In a third example of a configuration, the FBG sensor **300** can include an optical fiber, a stiff, rigid, or solid mounting, a housing, and FBGs **1-4**. FBGs **2** and **3**, which can be configured to operate at the same wavelength, can form a first phase-shift structure that can be used to sense pressure. The phase shift between FBGs **2** and **3** can result in a signal that changes with pressure or temperature, or both.

[0078] FBGs **1** and **4**, which can be configured to operate at the same wavelength, can form a second phase-shift structure that can be used to sense temperature. The reflections from FBG **4** interfere with the reflections from FBG **1** because of the phase shift between FBG **4** and FBG **1**, shown as a phase shift region **312**B in FIG. **3**. The phase shift between FBGs **1** and **4** can result in a signal that changes with temperature and that is independent of pressure.

[0079] A conceptual illustration of the response of FBGs **1-4** of the third example of a configuration is depicted in FIG. 4C, where the x-axis represents wavelength and the y-axis represents the intensity of the reflected light. As seen in FIG. 4C, the response includes two notches **418**, **420**. The third example of a configuration can provide more accurate measurements than the first example of a configuration because the notches **418**, **420** are generally more sensitive to any changes than responses without notches, e.g., the response **400** in FIG. 4A.

[0080] Similar to the first and second examples of configurations, in order to generate a pressure signal that is temperature compensated, the signal generated by FBGs **1** and **4** can be used as a reference, such as to null a shift in temperature. A slope **422** of the notch **418** and a slope **424** of the notch **420** can each be tracked and used to determine changes in temperature and pressure based on their respective changes in position. A controller circuit can be configured to control subtraction of the temperature reference signal (e.g., from FBG **1**) from the temperature and pressure signal (e.g., from FBGs **2** and **3**), such as to generate a temperature compensated pressure signal.

[0081] Using any one of the three examples of configurations described above, an optical fiber pressure sensor can be provided that can be suitable for delivery within a body lumen, e.g., for diagnostic assessment of coronary obstructions. In addition, any one of the three examples of configurations can compensate for temperature drift and can be fitted to a guidewire, such as for insertion into a body lumen of a patient. In any of the three examples the wavelength of the FBGs used for temperature calibration, compensation, or correction can be above or below the wavelength of the FBGs used for the pressure sensing.

[0082] Again, FIG. **3** is for conceptual purposes only and this disclosure is not limited to the three example configurations described above with respect to FIG. **3**. Other FBG configurations to sense pressure and compensate for temperature drift are possible, examples of which are described in more detail below.

[0083] In addition, as described in more detail below, various techniques are disclosed for increasing the intrinsic sensitivity of an optical fiber pressure sensor, such as to generate an accurate output signal within the range of pressures associated with a patient. Generally speaking, these techniques can include focusing a response of a pressure sensor membrane into a smaller area, such as to increase the optical response to the received pressure, e.g., from pressure waves.

[0084] FIGS. **4**A-**4**C depict various wavelength response diagrams related to the conceptual diagram and examples of configurations described above with respect to FIG. **3**. In FIGS. **4**A-**4**C, the x-axis represents wavelength and the y-axis represents the intensity of the reflected light. The response diagrams were described above in connection with the examples of configurations of FIG. **3**.

[0085] FIG. **5** is a block diagram of an example of an ambient temperature compensation technique that can be used to implement one or more techniques of this disclosure. Although the example of a configuration of FIG. **5**, shown generally at **500**, will be particularly described with specific reference to the third example of a configuration described above, it is applicable to each of the example configurations described in this disclosure.

[0086] Initially, the optical fiber pressure sensor **300** of FIG. **3** can be calibrated, such as to ascertain the relative coefficients of temperature and pressure for the sensor. The magnitudes of these coefficients can be stored in a memory device. A controller circuit can be configured such that, during operation, it can read the coefficients from the memory device and apply the pressure coefficient as a first coefficient X1 and the temperature coefficient as a second coefficient X2.

[0087] As described above, a first wavelength of a narrow band laser (in relation to the response of FBGs **1** and **4**) can be locked on a point on the slope **422** of the narrow transmission notch **418** in FIG. 4C, e.g., at about 50% of the length of the notch **418**. A second wavelength of a narrow band laser (in relation to the response of FBGs **2** and **3**) can be locked on a point on the slope **424** of the narrow transmission notch **420** in FIG. 4C, e.g., at about 50% of the depth of the notch **420**.

[0088] As the pressure changes, the notch **420** shifts and, consequently, the point on the slope **424** shifts. The tracking circuit can be configured to then track the point on the slope **424**. The magnitude of the change in wavelength, shown as λ1 in FIG. **5**, can be input into a first multiplier **502** and multiplied by the pressure coefficient X1. Similarly, as the ambient temperature of the pressure sensor changes, the notch **418** shifts and, consequently, the point on the slope **422** shifts. A tracking circuit can then track the point on the slope **422**. The magnitude of the change in wavelength, shown as λ2 in FIG. **5**, can be input into a second multiplier **504** and multiplied by the ambient temperature coefficient X2. Similarly, The outputs of the multipliers **502**, **504** can be input into a first comparator **506**, which can subtract any ambient temperature drift from the pressure measurement. In this manner, ambient temperature nulling techniques can be used to provide accurate pressure measurements.

[0089] Also in accordance with this disclosure, a third wavelength that can be close in magnitude to λ1 or λ2 but not in resonance with the phase shift feature can be used to monitor a total insertion loss of the system, e.g., from any bending, insertion of the optical fiber into a connector, etc. The insertion loss is generally a static number. During operation, the controller circuit can transmit the third wavelength λ3, which can be input into a second comparator **508** along with the pressure measurement output from a first comparator **506**, and the second comparator **508** can compensate the pressure measurement for any changes in insertion loss to produce a final pressure reading **510** for the optical fiber pressure sensor.

[0090] Pressure sensors constructed using optical fibers can suffer from significant pressure drift, due at least in part to the low intrinsic sensitivity of optical fibers (e.g., optical refractive index, mechanical size, etc.) to pressure. This is especially true for optical fiber pressure sensors that are designed for low pressure applications, such as sensing the pressure within the human body.

[0091] As mentioned above, when using an optical fiber pressure sensor capable of insertion into a body lumen of a patient, e.g., an animal such as a human, a small, uncompensated or uncorrected drift in temperature within the patient, e.g., as a result of an injected imaging contrast medium, can appear as an artifact that incorrectly indicates a large change in pressure. This can be due in part to the relatively low intrinsic sensitivity of the optical fiber pressure sensor to pressure and the relatively high intrinsic sensitivity to temperature of the optical fiber associated with the optical fiber pressure sensor. As such, a small, uncompensated drift in temperature can be unacceptable due to the need for accurate pressure measurements.

[0092] As described in more detail below with respect to FIGS. **6A-6B**, one or more techniques of this disclosure are described that can remove and/or compensate for the effects of temperature drifts and other deleterious effects that might compromise the accuracy of the pressure reading. For example, polarization scrambling techniques, ambient temperature nulling techniques, laser tracking techniques, and laser temperature monitoring techniques can be used in combination to correct for temperature drifts that can affect the accuracy of the pressure readings.

[0093] FIG. **6A** is a block diagram of an example of a laser tracking system, shown generally at **600**, in accordance with this disclosure. A controller circuit **602** can be configured to control a laser **604** to generate and transmit the light from a narrow band laser into a first port (e.g., port 1) of a circulator **606**. The circulator **606** can route the light out a second port (e.g., port 2) toward the optical fiber pressure sensor. The controller circuit **602** can be configured to set the wavelength of the laser on a point on a slope of a notch in the wavelength response of an FBG, such as described above. Any light reflected back from the optical fiber pressure sensor can enter the second port (e.g., port 2) of the circulator **606** and can be routed out a third port (e.g., port 3) and received by an optical detector **608**.

[0094] As indicated above, laser tracking techniques can be used to correct for temperature drift. In accordance with this disclosure, the laser **604** can be actively locked at a position on a slope of a transmission notch, e.g., slope **406** of the notch **402** of FIG. **4**A. Then, the system **600** can measure the change in wavelength and, in response, alter the laser's operating characteristics, e.g., drive current.

[0095] In the system **600** of FIG. **6**A, a first comparator **610** can be used to provide laser tracking The optical power of the reflected signal, which is output by the optical detector **608**, can be a first input to a first comparator **610**. A locking set point value **612** can be a second input to the first comparator **610**. The first comparator **610** can compare the two inputs and then output a value that can be applied as an input to a laser drive current control **614** that can modulate the drive current of the laser **604**. In this manner, the configuration of FIG. **6**A can provide a locking loop to maintain a set point on the slope of a notch, for example.

[0096] In one example implementation, during initial setup a user can adjust the conditions of the laser **604** so that the wavelength of the laser **604** is slightly greater than the wavelength of the transmission notch. The user can adjust the wavelength of the laser **604** by adjusting the drive current of a thermoelectric cooler (TEC) of the laser **604** (large shifts in wavelength), which can alter the temperature of a submount of the laser **604**, or adjust the drive current of the laser **604** itself (small shifts in wavelength).

[0097] Once the initial setup of the laser **604** is complete, the user can initiate the tracking techniques of this disclosure. The tracking techniques begin to reduce the drive current to the laser **604**, which, in turn, decrease the wavelength of the laser. More particularly, as the wavelength of the laser **604** decreases toward the wavelength of the transmission notch, the comparator **610** compares the signal from the optical detector **608** and the locking set point value **612**. If the signal from the optical detector **608** is higher than the locking set point value **612**, the drive current of the laser **604** can be reduced via feedback from the comparator **610** to the laser drive current control **614**. In some examples, reducing the laser drive current by 0.25 milliamps (mA) can shift the wavelength by 1 pm, where the coefficient of the laser **604** is about 4 pm per 1 mA of drive current.

[0098] During operation, the wavelength of the locked point on the slope can shift as the ambient temperature changes. If the wavelength of the transmission notch increases or decreases, the system **600** increases or decreases, respectively, the drive current of the laser **604** in order to track the transmission notch. As indicated above, the laser **604** can, for example, be locked on a point on a slope of the narrow transmission notch at about 50% of the depth of the notch **402**. These tracking techniques can track the position of the locked point on the slope and a change in temperature can be determined from the change in position. The determined change in temperature can be an input into an algorithm executed by a pressure reading module **622**, which can use the determined change in temperature to calculate an accurate pressure reading. The pressure reading module **622** can be, for example, machine or computer-implemented at least in part. For example, the controller **602** can execute instructions encoded on a computer-readable medium or machine-readable medium that implement the techniques and algorithms ascribed to the pressure reading module **622**.

[0099] One advantage of tracking the shift in wavelength of the FBG sensor by modulating the drive current of the laser is that it can linearize the response of the circuit and can be more forgiving of different power levels. That is, regardless of the insertion loss of the pressure sensor, which can vary by construction variables or variations in connecting in-line optical connectors, the amount by which the drive current will change for a given wavelength shift will be constant. Optical fiber pressure sensors that utilize a change in power to demodulate the signal are sensitive to changes in built in or fixed insertion loss. By knowing the shift in laser wavelength for a given drive current change, the current reading can be converted to a wavelength and hence to a pressure reading.

[0100] Optical sensing schemes exist that directly measure the change in wavelength of the sensor response. In one example, the sensor can be illuminated with broadband light and the spectral response can be measured with an Optical Spectrum Analyzer (OSA). This is not feasible for this application as the update times can be too slow and the required wavelength precision is beyond this type of instrument. Alternatively, techniques exist that measure the change in intensity of the optical power as the laser tracks up and down the slope of the FBG sensor. One disadvantage of this technique, however, is that the power response will be non-linear for large excursions as the laser approaches the top of the filter (lower slope) and the bottom of the filter (higher slope). Without compensation this technique can yield inaccurate results.

[0101] Continuing with the description of FIG. **6**A, the output of the first comparator **610** can be applied as a first input to a second comparator **616**. A zero pressure DC value **618** can be applied as a second input to the second comparator **616**, which can subtract the initial DC value and output a zero pressure reading. The outputted zero pressure reading from the second comparator **616** can be multiplied at a multiplier **620** by a coefficient of wavelength shift with the drive current that results in an output of an actual wavelength shift. The outputted actual wavelength shift can then be converted to a pressure reading at **622**.

[0102] As indicated above, laser temperature monitoring techniques can be used to correct for temperature drifts that can affect the accuracy of the pressure readings. The lasers used to implement the various techniques described in this application have a wavelength dependency on the temperature at which they operate. A typical laser will have a wavelength dependency on operating temperature of 100 pm per degree Celsius (° C.). A well controlled laser may have temperature stability of 0.01° C. giving a wavelength drift of 1 pm. As indicated above, however, a shift of 1 pm is equivalent to a very large pressure difference and, as such, should be accounted for in the final pressure reading.

[0103] Rather than stabilize the laser temperature to the degree required, which can increase the complexity and expense of the system **600**, this disclosure describes techniques that can accurately monitor the temperature through a thermistor that is built-in to the submount of the laser **604** and that can apply this temperature information to a correction algorithm for the final pressure reading **622**. To accurately monitor the temperature through the thermistor, the system **600** of FIG. **6**A can include an electronic circuit **624**, e.g., outside the optical system, that is configured to measure the voltage across the thermistor of the submount of the laser **604**. The electronic circuit **624** can include an amplifier that can amplify the voltage signal with high enough gain that to resolve temperature changes on the order of $1/1000^{th}$ of a degree Celsius. These changes are on the order of hundreds of microvolts (μV). As such, it can be desirable to use high quality circuits composed of instrumentation amplifiers, for example.

[0104] In one example implementation, rather than amplifying the voltage across the thermistor, the electronic circuit **624** can subtract an offset voltage from the voltage across the thermistor, e.g., the operating voltage of the laser, before amplification. Then, the electronic circuit **624** can amplify the resulting voltage value, which is close to zero. In this manner, the electronic circuit **624** allows small changes in the temperature of the laser to be determined. The temperature change can be converted to wavelength and then to the equivalent pressure, which can then be used to determine the true pressure reading at **622**.

[0105] The output from the laser, e.g., laser **604**, can have a strong degree of linear polarization at the exit from the laser package. It is technically possible to preserve this linear polarization by using polarization maintaining fiber and components along the entire optical path to the FBGs. If the polarization is preserved such that the light incident upon the FBGs is aligned preferentially with a particular birefringent axis, then the response of the light to the FBGs would not be affected by the birefringence. Unfortunately, preserving the polarization in this manner is both complex and expensive.

[0106] In the absence of polarization maintaining measures, the light from the laser can arrive at the FBGs with any state of polarization depending on the nature of the optical path through which the light has travelled. Significant bending or twisting of the fiber and the birefringent nature of any components through which the light has travelled can alter the state of polarization (SOP). Although the SOP that arrives at the FBGs is not controlled, it nevertheless can have a high degree of polarization (DOP) as this characteristic is very difficult to fully randomize. A high DOP means the exact interaction of the light and the birefringent axes of the FBGs can change if there are perturbations to the system, such as bending of the guidewire during a procedure. For this reason, the system **600** of FIG. **6**A can utilize polarization scrambling techniques to overcome the effects of birefringence and determine a true pressure reading. The polarization scrambling techniques scramble or average a range of polarization states so the final result is not biased to any given combination of birefringent axis of the FBG and incident polarization state.

[0107] Optical fiber pressure sensors such as the FBGs of this disclosure are subject to the effects of birefringence in the optical fiber, due to the physical imperfections of the fiber. With birefringence, different polarizations of light can have slightly different effective optical refractive indices. An effective index of the fiber that is different for different polarizations can result in a slightly different Bragg wavelength. A different Bragg wavelength can result in the appearance of movement of the point on the slope of the transmission notch at which the laser is locked. In reality, however, the point may not have moved at all.

[0108] A typical optical fiber can have birefringence on the order of 2.5×10^{-6}, which translates to a wavelength shift between the most different polarizations of 4 pm. A 4 pm wavelength shift would be equivalent to a relatively massive pressure change and, as such, should be accounted for in the final pressure reading.

[0109] The exact wavelength of the FBG can be determined by a combination of the refractive index of the medium and the physical spacing of the planes or fringes that make up the FBG, as in the following equation:

$1_B=2n_eL$, where 1_B=Bragg wavelength, n_e=effective refractive index, and L=spacing of fringes.

[0110] The polarization scrambling techniques of this disclosure can be implemented by sweeping a series of "optical waveplates" through a pseudo-random pattern with sufficient frequency that the desired signal will be averaged satisfactorily. Optical waveplates are devices that can alter the state of polarization. In order to measure a typical cardiovascular pressure profile with a heart rate of 0 beats per minute to 200 beats per minute, scrambling techniques can average at a rate that is sufficient to capture the dynamic profile, e.g., an effective frequency of several hundred hertz.

[0111] In the system **600** of FIG. **6**A, the optical waveplates can be physically located between where the laser beam exits laser **604** and the FBGs of the optical fiber pressure sensor. In one example, an optical waveplate can be formed by wrapping a portion of the optical fiber around a piezoelectric material and by stretching the fiber upon application of a voltage to the piezoelectrical material. In another example, an optical waveguide can be used to form an optical waveplate. The application of a voltage across electrodes built into the optical waveguide can result in the change of the refractive index.

[0112] Using the polarization scrambling techniques of this disclosure, it is not necessary to know the levels or patterns of birefringence in the system because the polarization controlling techniques do not rely upon feedback. Instead, the polarization scrambling techniques rely on an averaged polarization that is achieved by sweeping through as many available polarization states to get an average polarization value so the final result is not biased to any given combination of birefringent axis of the FBG and incident polarization state. Additional information regarding how the polarization scrambling techniques are used to determine a true pressure reading are disclosed in U.S. Provisional Application No. 61/709,700, titled "POLARIZATION SCRAMBLING FOR INTRA-BODY FIBER OPTIC SENSOR", by Howard Rourke, et al. and filed on Oct. 4, 2012, the entire content of which being incorporated herein by reference.

[0113] FIG. **6**B is a block diagram of an example of a temperature compensation technique in accordance with this disclosure. As described above, in order to determine an accurate pressure reading, both the ambient temperature of the optical fiber pressure sensor and the temperature drift of the laser should be accounted for in the final pressure reading at **622** of FIG. **6**A. In FIG. **6**B, a first laser **630** can be locked onto a phase-shift region, e.g., phase-shift region **312**A between FBG **2** and FBG **3** of FIG. **3**. This phase-shift region, however, is not compensated for the ambient temperature of the pressure sensor and, as such, reacts to both pressure and temperature. Using either a measurement of the change in drive current of the laser, e.g., in milliamps, or a measurement of the change in wavelength, the controller **602** of FIG. **6**A can determine the shift in wavelength at **632**. Further, using the techniques described above, the controller **602** can determine the operating temperature of the first laser **630** at **634** by measuring the voltage across the submount thermistor via the electronic circuit **624** of FIG. **6**A. The controller **602** can correct the determined shift in wavelength for the operating temperature of the first laser **630** by subtracting the determined operating temperature of the first laser **630** from the shift in wavelength determined at **636**. Next, the corrected wavelength shift can be scaled to an equivalent pressure at **638**, e.g., converted from a voltage value to a pressure value. The corrected wavelength shift at **636** and its scaled value at **638**, however, have not been corrected for the ambient temperature of the pressure sensor.

[0114] In order to correct for the ambient temperature of the pressure sensor, a second laser **640** can be locked onto another phase-shift region, e.g., phase-shift region **312**B between FBG **1** and FBG **4** of FIG. **3**. This phase-shift region is insensitive to pressure and responds only to the ambient temperature of the pressure sensor. Using either a measurement of the change in drive current of the laser, e.g., in milliamps, or a change in wavelength, the controller **602** of FIG. **6**A can determine the shift in wavelength at **642**. The controller **602** can also determine the temperature of the second laser **640** at **644** by measuring the voltage across the submount thermistor via the electronic circuit **624** of FIG. **6**A. The controller **602** can correct the determined shift in wavelength for the operating temperature of the second laser **640** by subtracting the determined operating temperature of the second laser **640** from the shift in wavelength determined at **646**. Next, the corrected wavelength shift can be scaled to an equivalent pressure at **648**, e.g., converted from a voltage value to a pressure value. Finally, at **650**, the pressure determined at **648** can be subtracted from the pressure determined at **638** in order to determine a true pressure reading.

[0115] FIGS. **7**A-**7**C depict an example of a pressure sensor that can be used to implement one or more techniques of this disclosure. The example of the pressure sensor depicted in FIGS. **7**A-**7**C is an example of a standalone pressure sensor that can use one or more phase shift gratings. The type of grating written into the fiber can be, for example, a "phase shift" grating or a "Fabry Perot" grating. A "standalone" sensor can be capable of sensing pressure independently of the fiber being attached to a guide wire core subassembly. In contrast, an "integrated" pressure sensor can involve placing the fiber with the appropriate gratings written in it on a guide wire core and then completing the sensor once the fiber is positioned on the wire.

[0116] FIG. 7A is an example of a perspective view of an example of a optical fiber pressure sensor **700** that can include an optical fiber **702**, which can be configured to transmit one or more optical sensing signals, and a temperature compensated Fiber Bragg Grating (FBG) interferometer (shown generally at **704** in FIG. 7C) that can be included in, or in optical communication with, the optical fiber **702**. The FBG interferometer **704** can be configured to receive pressure (e.g., from pressure waves), and to modulate, in response to the received pressure, an optical sensing signal being delivered via the optical fiber **702** to the FBG interferometer **704**. The pressure sensor **700** can include a sensor membrane **706**, which can be in physical communication with the FBG interferometer **704**. The sensor membrane **706** can be configured to help transmit the pressure to the FBG interferometer **704**. The pressure sensor **700** can further include a sheath **708** that can, for example, help contain components of the pressure sensor **700** and/or help ease the pressure sensor through the vascular system.

[0117] FIG. 7B is an example of a cross-sectional end view of the pressure sensor **700** of FIG. 7A. As seen in FIG. 7B, the optical fiber **702** can extend through the pressure sensor **700**, such as at substantially an axial center of the pressure sensor **700**.

[0118] FIG. 7C is an example of a cross-sectional side view of the pressure sensor **700** of FIG. 7A, such as can be taken along section A-A of FIG. 7B. FIG. **7**C depicts the optical fiber **702** extending through a proximal portion **710** and a distal portion **712** of the pressure sensor **700**. A proximal portion of the phase shift grating of FBG interferometer **704** can be captured by a stiff, rigid, or solid supporting member **714**, e.g., via bonding. The supporting member **714** can be a capillary tube, for example.

[0119] In the distal portion **712**, the pressure sensor **700** can define a cavity **716**, e.g., filled with air, such as laterally below the distal portion of the phase shift grating of FBG interferometer **704** and laterally below the remaining distal length of the fiber **702** extending distally axially beyond the phase shift grating. In the example shown in FIG. **7**C, the flexible sensor membrane **706** can be thick enough such that it contacts the fiber **702** and the fiber **702** can be attached to the flexible sensor membrane **706**, e.g., via bonding. The flexible sensor membrane **706** can include, for example, a thin polymer film, a heat seal film, or a thin metal foil. The flexible sensor membrane **706** can be attached to the pressure sensor **700**, such as via bonding or solder. In an example, the membrane **706** can be made by casting a silicone layer.

[0120] The pressure sensor **700** can be sealed on both the proximal end **718** and the distal end **720**. In addition, the sensor membrane **706** can be sealed creating the sealed cavity **706**.

[0121] The example pressure sensor **700** of FIG. **7**C depicts three FBGs, namely FBGs **1**-**3**, along with an optional FBG, namely FBG **4**. FBG **1** is independent of pressure and can be used for temperature measurements to provide a temperature compensated optical fiber pressure sensor, as described above with respect to FIG. **3** and FIG. **4**A.

[0122] FBGs **2** and **3** can form a phase-shift FBG structure. The surface area of the membrane **706** can concentrate a change in pressure and can focus a mechanical response to the change in pressure at the phase-shift region between FBG **2** and FBG **3**. This can enhance the sensitivity of the pressure sensor **700**. The mechanical forces acting upon the phase-shift region between FBG **2** and FBG **3** can concentrate a stress in the phase-shift region. The concentrated stress in the phase-shift region can change the refractive index of the optical fiber **702**, which, in turn, alters the phase relationship between FBG **2** and FBG **3**. The change in phase-shift between FBG **2** and FBG **3** can be detected and quantified, and the change in pressure can be determined from the quantified phase-shift.

[0123] In an example, the pressure sensor **700** can optionally further include FBG **4**, e.g., located axially more proximal than FBG **1**. As described above with respect to FIG. **3** and FIG. **4**C, FBGs **1** and **4** can form a phase-shifted FBG structure that can be used to detect and quantify a change in temperature in the pressure sensor **700**, which can be substantially independent of any pressure variations, due to the location of FBGs **1** and **4** within the stiff, rigid, or solid supporting member **714**. In the configuration shown in FIG. **7**C, the supporting member **714** can be disposed about FBGs **1**, **2**, and **4**.

[0124] FIGS. **8**A-**8**C depict another example of a pressure sensor that can be used to implement one or more techniques of this disclosure, such as can use a standalone pressure sensor that can use one or more phase shift gratings.

[0125] FIG. **8**A is a perspective view of an example of an optical fiber pressure sensor **800** that can include an optical fiber **802**, which can be configured to transmit one or more optical sensing signals, and a temperature compensated Fiber Bragg Grating (FBG) interferometer (shown generally at **804** in FIG. **8**C) in optical communication with the optical fiber **802**. The FBG interferometer **804** can be configured to receive pressure (e.g., from pressure waves), and to modulate, in response to the received pressure, the optical sensing signal. The pressure sensor **800** can include a sensor membrane **806** that can be in physical communication with the FBG interferometer **804**. The sensor membrane **806** can be configured to transmit the pressure to the FBG interferometer **804**. The pressure sensor **800** can further include a sheath **808** that can, for example, help contain components of the pressure sensor **800** and/or help ease the pressure sensor through the vascular system.

[0126] FIG. **8**B is an example of a cross-sectional end view of the pressure sensor **800** of FIG. **8**A. As seen in FIG. **8**B, the optical fiber **802** can extend through the pressure sensor **800**, such as at substantially an axial center of the pressure sensor **800**.

[0127] FIG. **8**C is an example of a cross-sectional side view of the pressure sensor **800** of FIG. **8**A, such as can be taken along section A-A of FIG. **8**B. The optical fiber **802** can be supported in part by a stiff, rigid, or solid supporting member **814**. The pressure sensor **800** can define a cavity **816**, e.g., filled with air.

[0128] As seen in FIG. **8**C, the sensor membrane **806** can include a tapered portion **818** that can extend inwardly toward an axial center of the pressure sensor **804**. The tapered portion **818** can help focus the response of the membrane **806** against the phase-shift region between FBG **2** and FBG **3**, thereby further concentrating a stress in the phase-shift region, which can enhance the sensitivity of the pressure sensor **800**.

[0129] In an example, a portion of the supporting member **814** can define a reservoir **820** that can be adjacent to the fiber **802**. The reservoir **820** can be filled with a gas, e.g., air. In one example, the reservoir can be filled with a gas, e.g., nitrogen, that can provide greater temperature stability than air. In one example, the reservoir **820** can be a vacuum that can provide temperature stability. The reservoir **820** can provide a configuration that can be adjacent a limited cavity **816** immediately laterally below the fiber **802** between FBG **2** and FBG **3** such that it can be acted upon by the portion **818** yet the reservoir **820** still includes a large compressible volume.

[0130] In an example, such as shown in FIG. **8**C, the flexible sensor membrane **806** can include, for example, a thin polymer film, a heat seal film, or a thin metal foil. The flexible sensor membrane **806** can be attached to the pressure sensor **800**, such as via bonding or solder. In an example, the membrane **806** can be made by casting a silicone layer.

[0131] The pressure sensor **800** can be sealed on both the proximal end **817** and the distal end **819**. The sensor membrane **806** can be sealed, such as for creating the sealed cavity **816**.

[0132] The example of a pressure sensor **800** of FIG. **8**C can include three FBGs (e.g., FBGs **1**-**3**) along with an optional FBG (e.g., FBG **4**). FBG **1** can be configured to be independent of pressure and can be used for temperature measurement, such as to provide a temperature compensated optical fiber pressure sensor, such as described above with respect to FIG. **3** and FIG. **4**A.

[0133] FBGs **2** and **3** can form a phase-shifted FBG structure. The surface area of the membrane **806** can be configured to concentrate a change in pressure onto the portion **818**, which can focus a mechanical response to the pressure at the phase-shift region between FBG **2** and FBG **3**. The mechanical force acting upon the phase-shift region between FBG **2** and FBG **3** can concentrate a stress in the phase-shift region. The concentrated stress in the phase-shift region can change the refractive index of the optical fiber **802**, such as to alter the phase relationship between FBG **2** and FBG **3**. The change in phase-shift between FBG **2** and FBG **3** can be detected and quantified, and the change in pressure can be determined from the quantified phase-shift.

[0134] The pressure sensor **800** can optionally further include FBG **4**, e.g., located axially more proximal than FBG

1. As described above with respect to FIG. **3** and FIG. **4**C, FBGs **1** and **4** can form a phase-shifted FBG structure that can be used to detect and quantify a change in temperature in the pressure sensor **800**. In the configuration shown in FIG. **8**C, the supporting member **814** is not disposed about FBGs **1**, **2**, and **4**, in contrast to the configuration example of FIG. **7**C.

[0135] FIGS. **9**A-**9**C depict another example of a pressure sensor that can be used to implement one or more techniques of this disclosure. The example of the pressure sensor depicted in FIGS. **9**A-**9**C can provide a standalone pressure sensor that can use one or more phase shift gratings.

[0136] FIG. **9**A is a perspective view of an optical fiber pressure sensor **900** that can include an optical fiber **902**, which can be configured to transmit one or more optical sensing signals, and a temperature compensated Fiber Bragg Grating (FBG) interferometer (shown generally at **904** in FIG. **9**C), such as in optical communication with the optical fiber **902**. The FBG interferometer **904** can be configured to receive pressure (e.g., from pressure waves), and to modulate, in response to the received pressure, the optical sensing signal. The pressure sensor **900** can include a sensor membrane **906** that can be in physical communication with the FBG interferometer **904**. The sensor membrane **906** can be configured to transmit the pressure to the FBG interferometer **904**. The pressure sensor **900** can further include a sheath **908** that can, for example, help contain components of the pressure sensor **900** and/or help ease the pressure sensor through the vascular system.

[0137] FIG. **9**B is an example of a cross-sectional end view of the pressure sensor **900** of FIG. **9**A. As seen in FIG. **9**B, the optical fiber **902** can extend through the pressure sensor **900** at a position that is offset from an axial center of the pressure sensor **900**.

[0138] FIG. **9**C is an example of a cross-sectional side view of the pressure sensor **900** of FIG. **9**A, such as can be taken along section A-A of FIG. **9**B. FIG. **9**C depicts the optical fiber **902** extending through a proximal portion **910** and a distal portion **912** of the pressure sensor **904**. A proximal portion of the FBG interferometer **904** can be captured by a supporting member **914**, e.g., via bonding. The supporting member **914** can include a capillary tube, for example. In the distal portion **912**, the pressure sensor **900** can define a cavity **916**, e.g., filled with air.

[0139] As seen in the example shown in FIG. **9**C, the sensor membrane **906** can be in mechanical communication with a portion **921** that can extend laterally inwardly into the pressure sensor **904**. The portion **921** can focus the response of the membrane **906** against the phase-shift region between FBG **2** and FBG **3**, which can thereby further concentrate a stress in the phase-shift region, which can enhance the sensitivity of the pressure sensor **900**.

[0140] In the example shown in FIG. **9**C, the flexible sensor membrane **906** can include, for example, a thin polymer film, a heat seal film, or a thin metal foil. The flexible sensor membrane **806** can be attached to the pressure sensor **900**, such as via bonding or solder. In an example, the membrane **906** can be made by casting a silicone layer.

[0141] The pressure sensor **900** can be sealed on both the proximal end **918** and the distal end **920**. In addition, the sensor membrane **906** can be sealed creating the sealed cavity **916**.

[0142] The example of a pressure sensor **900** of FIG. **9**C can include three FBGs (e.g., FBGs **1**-**3**), along with an optional FBG (e.g., FBG **4**). FBG **1** can be configured to be independent of pressure, such as explained above, and can be used for temperature measurement, such as to provide a temperature compensated optical fiber pressure sensor, such as described above with respect to FIG. **3** and FIG. **4**A.

[0143] FBGs **2** and **3** can form a phase-shifted FBG structure. The surface area of the membrane **906** can concentrate any change in pressure into the portion **921**, which can focus a mechanical response to the pressure at the phase-shift region between FBG **2** and FBG **3**. The mechanical forces acting upon the phase-shift region between FBG **2** and FBG **3** can concentrate a stress in the phase-shift region. The concentrated stress in the phase-shift region can change the refractive index of the optical fiber **902**, such as to alter the phase relationship between FBG **2** and FBG **3**. The change in phase-shift between FBG **2** and FBG **3** can be detected and quantified, and the change in pressure can be determined from the quantified phase-shift. The pressure sensor **900** can include a compliant layer **919** laterally underneath the optical fiber **902**, such as to allow the portion **921** to act on the optical fiber **902** without damaging the optical fiber **902**.

[0144] The pressure sensor **900** can optionally further include FBG **4**, e.g., located more proximal than FBG **1**. As described above with respect to FIG. **3** and FIG. **4**C, FBGs **1** and **4** can form a phase-shifted FBG structure that can be used to quantify a change in temperature in the pressure sensor **800**. In the configuration shown in FIG. **9**C, the supporting member **914** can be disposed about FBGs **1** and **4**.

[0145] FIGS. **10**A-**10**D depict an example of a pressure sensor that can be used to implement one or more techniques of this disclosure. The example of a pressure sensor depicted in FIGS. **10**A-**10**D can provide an example standalone pressure sensor that can use one or more "Fabry Perot" grating arrangements.

[0146] FIG. **10**A is an example of a perspective view of an optical fiber pressure sensor **1000** that can include an optical fiber **1002**, which can be configured to transmit one or more optical sensing signals, and a temperature compensated Fiber Bragg Grating (FBG) interferometer (shown generally at **1004** in FIG. **10**D) that can be in optical communication with the optical fiber **1002**. The FBG interferometer **1004** can be configured to receive pressure (e.g., from pressure waves), and to modulate, in response to the received pressure, the optical sensing signal. The pressure sensor **1000** can include a sensor membrane **1006** that can be in physical communication with the FBG interferometer **1004**. The sensor membrane **1006** can be configured to transmit the pressure to the FBG interferometer **1004**. The pressure sensor **1000** can further include a sheath **1008** that can, for example, help contain components of the pressure sensor **1000** and/or help ease the pressure sensor through the vascular system.

[0147] FIG. **10**B is an example of a cross-sectional end view of the pressure sensor **1000** of FIG. **10**A, depicting an example of a location of the optical fiber **1002**. As seen in the example of FIG. **10**B, the optical fiber **1002** can extend axially through the pressure sensor **1000**, such as at a position that is axially offset from an axial center of the pressure sensor **1000**. FIG. **10**C is an example of a cross-sectional end view of the pressure sensor without the optical fiber **1002**.

[0148] FIG. **10**D is an example of a cross-sectional side view of the pressure sensor **1000** of FIG. **10**A, such as can be taken along section A-A of FIG. **10**C. FIG. **10**D depicts an example of the optical fiber **1002** extending through a proximal portion **1010** and a distal portion **1012** of the pressure sensor **1004**. A proximal portion of the optical fiber **1002** can be captured by a first supporting member **1014**A and a distal portion **1012** of the optical fiber **1002** can be captured by a second supporting member **1014**B, e.g., via bonding.

[0149] The pressure sensor **1000** can include a sensor membrane **1006**. The pressure sensor **1000** can define a cavity **1016**, e.g., filled with air, laterally below the sensor membrane **1006**. The sensor membrane **1006** and the cavity **1016** can concentrate a stress in the area between the Fabry-Perot gratings FBG **1** and FBG **2**, which can enhance the sensitivity of the pressure sensor **1000**.

[0150] The flexible sensor membrane **1006** can include, for example, a thin polymer film, a heat seal film, or a thin metal foil. The flexible sensor membrane **1006** can be attached to the pressure sensor **1000**, such as via bonding or solder. In an example, the membrane **1006** can be made by casting a silicone layer.

[0151] The pressure sensor **1000** can be sealed on both the proximal end **1018** and the distal end **1020**. The sensor membrane **1006** can be sealed, such as for creating the sealed cavity **1016**.

[0152] The example of a pressure sensor **1000** of FIG. **10**D can include four FBGs (e.g., FBGs **1-4**). FBGs **3** and **4** can form a phase-shifted FBG structure, such as for sensing temperature. The change in phase-shift between FBG **3** and FBG **4** can be detected and quantified, and the change in temperature can be determined from the quantified phase-shift, such as described above.

[0153] The pressure sensor **1000** can further include Fabry-Perot gratings FBG **1** and FBG **2**, which can be used to sense changes in pressure. Similar to the phase-shift grating structures described above with respect to FIGS. **7-9**, the Fabry-Perot gratings FBG **1** and FBG **2** can create a phase shift that can be tracked in a manner similar to that described above. That is, a notch can be created in the wavelength response to the Fabry-Perot gratings FBG **1** and FBG **2**, as shown and described in more detail with respect to FIG. **11**. A point on a slope of the notch can be set and tracked, a phase shift can be detected and quantified, and the change in pressure can be determined from the quantified phase-shift, such as described in detail above.

[0154] FIG. **11** depicts an example of a conceptual response diagram related to the example of a pressure sensor shown in FIG. **10**D. In particular, FIG. **11** depicts a conceptual wavelength response of the Fabry-Perot gratings FBG **1** and FBG **2** of FIG. **10**D. As seen in the example shown in FIG. **11**, the wavelength response of the Fabry-Perot gratings FBG **1** and FBG **2** can include three notches, **1100**, **1102**, **1104**. This is in contrast to the wavelength responses of the phase-shift structures shown in FIGS. **4**A-**4**C, which can include a single notch for a pair of FBGs. The additional notches in FIG. **11** can be a result of the increased distance between the Fabry-Perot gratings FBG **1** and FBG **2**. As the distance between the Fabry-Perot gratings FBG **1** and FBG **2** increases, additional notches can occur. As the distance between the Fabry-Perot gratings FBG **1** and FBG **2** decreases, notches can disappear until the response resembles that of the phase-shift structures described above.

[0155] In a manner similar to that described above, a wavelength of a narrow band laser (in relation to the response of FBGs **1** and **2**) can be locked on a point on a slope **1106** of a narrow transmission notch, e.g., notch **1102**, in FIG. **11**, e.g., at about 50% of the length of the notch **1102**. As the pressure changes, the notch **1102** and, consequently, the point on the slope **1106** shifts. A tracking circuit can then track the point on the slope **1106** and a phase-shift can be determined from its change in position. The intensity of reflected light will be modified when the notch **1106** moves. A phase shift can be quantified, and the change in pressure can be determined from the quantified phase-shift, such as described in detail above.

[0156] FIGS. **12**A-**12**C depict another example of a pressure sensor that can be used to implement one or more techniques of this disclosure. The example of a pressure sensor depicted in FIGS. **12**A-**12**C can provide another example standalone pressure sensor that can use one or more Fabry-Perot grating arrangements.

[0157] FIG. **12**A is an example of a perspective view of an optical fiber pressure sensor **1200** that can include an optical fiber **1202** that can be configured to transmit one or more optical sensing signals and a temperature compensated Fiber Bragg Grating (FBG) interferometer (shown generally at **1204** in FIG. **12**C) in optical communication with the optical fiber **1202**. The FBG interferometer **1204** can be configured to receive pressure, e.g., from pressure waves, and to modulate, in response to the received pressure, the optical sensing signal. The pressure sensor **1200** can include a sensor membrane **1206** that can be in physical communication with the FBG interferometer **1204**. The sensor membrane **1206** can be configured to transmit the pressure to the FBG interferometer **1204**. The pressure sensor **1200** can further include a sheath **1208** that can, for example, help contain components of the pressure sensor **1200** and/or help ease the pressure sensor through the vascular system.

[0158] FIG. **12**B is an example of a cross-sectional end view of the pressure sensor **1200** of FIG. **12**A. As seen in FIG. **12**B, the optical fiber **1202** can extend axially through the pressure sensor **1200** such as at substantially an axial center of the pressure sensor **1200**.

[0159] FIG. **12**C is an example of a cross-sectional side view of the pressure sensor **1200** of FIG. **12**A, such as can be taken along section A-A of FIG. **12**B. The optical fiber **1202** can be supported in part by supporting members **1214**A, **1214**B. The pressure sensor **1200** can define a cavity **1216**, e.g., filled with air.

[0160] As seen in the example of FIG. **12**C, the sensor membrane **1206** can include a portion **1218** that can extend inwardly toward a center of the pressure sensor **1204** and that can taper, such as to a point. The portion **1218** can focus the response of the membrane **1206** against the area between FBG **1** and FBG **2**, such as for thereby further concentrating a stress in the phase-shift region, which can enhance the sensitivity of the pressure sensor **1200**.

[0161] A portion of the supporting member **1214** can define a reservoir **1220**, such as laterally below the area extending axially between FBG **1** and FBG **2**. The reservoir **1220** can further enhance the sensitivity of the pressure sensor **1200**, such as by allowing the area between FBG **1** and FBG **2** to deflect into the reservoir **1220**.

[0162] In the example shown in FIG. **12**C, the flexible sensor membrane **1206** can include, for example, a thin polymer film, a heat seal film, or a thin metal foil. The flexible sensor membrane **1206** can be attached to the pressure sensor **1200**, such as via bonding or solder. In an example, the membrane **1206** can be made by casting a silicone layer.

[0163] The pressure sensor **1200** can be sealed, such as on both the proximal end **1222** and the distal end **1224**. The sensor membrane **1206** can be sealed, such as for creating the sealed cavity **1216**.

[0164] The example of a pressure sensor **1200** of FIG. **12**C can include two FBGs (e.g., Fabry-Perot gratings FBG **1** and FBG **2**), which can be used to sense changes in pressure, such as described above with respect to FIG. **10**D. The pressure sensor **1200** can optionally further include one or more temperature compensating FBGs. For example, the pressure sensor **1200** can include two additional FBGs (e.g., FBGs **3** and **4** of FIG. **10**D), which can form a phase-shifted FBG structure, such as for sensing temperature. The change in phase-shift between FBG **3** and FBG **4** can be quantified and the change in temperature can be determined from the quantified phase-shift, such as described above.

[0165] FIGS. **13**A-**13**C depict an example of a guidewire in combination with an optical pressure sensor. FIG. **13**A is an example of a perspective view illustrating a combination **1300** of a guidewire **1302** and an optical fiber **1304** attached to an optical fiber pressure sensor. An optical fiber pressure sensor can be attached at a distal end of the guidewire **1302**. The optical fiber **1304** can be disposed in a smooth, rounded groove (groove **1306** of FIG. **13**C) extending axially along an outer diameter of the guidewire **1302** and optionally helically wound about the guidewire **1302**, such as within a helically axially extending groove. FIG. **13**B is an example of a cross-sectional side view of the combination **1300** of FIG. **13**A, illustrating the optional helical pitch of the combination.

[0166] FIG. **13**C is an example of a cross-sectional end view of the combination **1300** of FIG. **13**A, such as can be taken along section A-A of FIG. **13**B. The guidewire **1302** can include a solid guidewire with a smooth, rounded groove **1306** etched out, for example, of the guidewire material (or etched out of a coating thereupon), thereby preserving most of the guidewire material, which can help preserve its mechanical properties. In this manner, the guidewire can be substantially solid, which can avoid the kinking issues that can be associated with hollow guidewires. Using a substantially solid guidewire can improve the guidewire's torque capabilities. In an example, a coating can be applied over the guidewire **1302** and over the fiber **1304**, such as to help protect the fiber **1304** or to help secure the fiber **1304** to the guidewire **1302**.

[0167] FIGS. **14**A-**14**C depict an example of a guidewire in combination with an optical fiber pressure sensor. FIG. **14**A is an example of a perspective view illustrating a combination **1400** of a guidewire **1402** and an optical fiber **1404** that can be attached to an optical fiber pressure sensor. An optical fiber pressure sensor can be attached at a distal end of the guidewire **1402**. The optical fiber **1402** can be disposed in a flat groove (flat groove **1406** of FIG. **14**C) extending axially along an outer diameter of the guidewire **1402** (or along a coating thereupon) and optionally helically wound about the guidewire **1402**. FIG. **14**B is a cross-sectional side view of the combination **1400** of FIG. **14**A, illustrating the helical pitch of the combination. The helical design can allow any stresses, e.g., from compression and tension, to be more evenly distributed along the length of the guidewire.

[0168] FIG. **14**C is a cross-sectional end view of the combination **1400** of FIG. **14**A, such as can be taken along section A-A of FIG. **14**B. The guidewire **1402** can include a solid guidewire with a flat groove **1406** etched out, for example, of the guidewire material, or a coating thereupon, thereby preserving most of the guidewire material and the mechanical properties associated therewith. In this manner, the guidewire can be substantially solid, which can help avoid the kinking issues that can be associated with hollow guidewires. Using a substantially solid guidewire can provide better torque capability of the guidewire. In an example, a coating can be applied over the guidewire **1402** and the fiber **1404**, such as to help protect the fiber **1404** or to help secure the fiber **1404** to the guidewire **1402**.

[0169] FIGS. **15**A-**15**C depict an example of a guidewire in combination with an optical fiber pressure sensor. FIG. **15**A is an example of a perspective view illustrating a combination **1500** of a multifilar guidewire **1502** and an optical fiber **1504** that can be attached to an optical fiber pressure sensor. An optical fiber pressure sensor can be attached at a distal end of the guidewire **1502**. The optical fiber **1504** can be disposed in an interstice between filaments of the multifilar guidewire **1502** and optionally axially helically wound about the guidewire **1502**. FIG. **15**B is an example of a cross-sectional side view of the combination **1500** of FIG. **15**A, illustrating an example of the helix pitch of the combination.

[0170] FIG. **15**C is an example of a cross-sectional end view of the combination **1500** of FIG. **15**A, such as can be taken along section A-A of FIG. **15**B. The multifilar guidewire **1502** can include multiple filaments **1506**. The optical fiber **1504** can be disposed in an interstice between two filaments **1506**, for example, toward an outer diameter of the guidewire **1502**. In this manner, the guidewire can be substantially rigid, like a solid guidewire, which can help avoid the kinking issues that can be associated with hollow guidewires. Using a substantially solid guidewire can help provide desired torque capability of the guidewire. In an example, a coating can be applied over the guidewire **1502** and the fiber **1504**, such as to help protect the fiber **1504** or to help secure the fiber **1504** to the guidewire **1502**.

[0171] FIG. **16** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure. The example of a pressure sensor depicted in FIG. **16** can provide an example of an integrated pressure sensor that can use one or more Fabry-Perot grating arrangements. Again, an "integrated" pressure sensor can involve placing the fiber with the appropriate gratings written in the fiber on a guidewire and then completing the sensor once the fiber is positioned on the wire.

[0172] FIG. **16** is an example of a perspective cross-sectional view of an optical fiber pressure sensor **1600** that can include an optical fiber **1602** that can be configured to transmit one or more optical sensing signals and a temperature compensated Fiber Bragg Grating (FBG) interferometer **1604** in optical communication with the optical fiber **1602**. The FBG interferometer **1604** can be configured to receive pressure, e.g., from pressure waves, and to modulate, in response to the received pressure, the optical sensing signal. The pressure sensor **1600** can include a sensor membrane **1606** that can be in physical communication with the FBG interferometer **1604**. The sensor membrane **1606** can be configured to transmit the pressure to the FBG interferometer **1604**.

[0173] The example of a pressure sensor **1600** of FIG. **16** can further include Fabry-Perot gratings FBG **1** and FBG **2**, which can be used to sense changes in pressure. The Fabry-Perot gratings FBG **1** and FBG **2** can create a phase shift that can be tracked in a manner similar to that described above.

[0174] The pressure sensor **1600** of FIG. **16** can further include a proximal coil **1608** and a distal coil **1610**. The proximal and distal coils **1608**, **1610** can provide flexibility to aid advancement of the pressure sensor **1600** through tortuous pathways. In one example, the proximal and distal coils **1608**,

1610 can be affixed together via a mechanical joint (not depicted), e.g., via solder or adhesive. The FBG interferometer **1604** can, in some examples, be positioned underneath the mechanical joint to provide additional protection to the FBG interferometer **1604**.

[0175] The pressure sensor **1600** of FIG. **16** can further include a guidewire **1612** to which the optical fiber **1602** can be attached. In the example depicted in FIG. **16**, a portion of the guidewire **1612** can define a machined gap (not depicted) underneath the proximal coil **1608**. The machined gap can allow the optical fiber **1602** to extend longitudinally or helically along the outer surface of the guidewire **1612** and then transition underneath the proximal coil gradually into the machined gap.

[0176] The guidewire **1612** can also define cavity **1614**, e.g., filled with air, laterally below the sensor membrane **1606**. The sensor membrane **1606** and the cavity **1614** can concentrate a stress in the area between the Fabry-Perot gratings FBG **1** and FBG **2**, which can enhance the sensitivity of the pressure sensor **1600**. The optical fiber **1602** can be securely attached to the guidewire **1612** on each side of the cavity **1614**. In addition, the sensor membrane **1606** can be sealed 360 degrees around the guidewire **1612** at an optical fiber entry end **1616** of the sensor membrane **1606** and at a distal end **1618** of the optical fiber **1602** and along the edges of the membrane **1606**.

[0177] FIG. **17** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure. FIG. **17** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure. The example of a pressure sensor **1700** depicted in FIG. **17** can provide an example standalone pressure sensor that can use one or more Fabry-Perot grating arrangements.

[0178] FIG. **17** is an example of a perspective cross-sectional view of an optical fiber pressure sensor **1700** that can include an optical fiber **1702** that can be configured to transmit one or more optical sensing signals and a temperature compensated Fiber Bragg Grating (FBG) interferometer **1704** in optical communication with the optical fiber **1702**. The FBG interferometer **1704** can be configured to receive pressure, e.g., from pressure waves, and to modulate, in response to the received pressure, the optical sensing signal. The pressure sensor **1700** can include a sensor membrane **1706** that can be in physical communication with the FBG interferometer **1704**. The sensor membrane **1706** can be configured to transmit the pressure to the FBG interferometer **1704**.

[0179] The example of a pressure sensor **1700** of FIG. **17** can include four FBGs (e.g., FBGs **1**-**4**.) FBGs **3** and **4** can form a phase-shifted FBG structure, such as for sensing temperature. The change in phase-shift between FBG **3** and FBG **4** can be detected and quantified, and the change in temperature can be determined from the quantified phase-shift, such as described above.

[0180] The pressure sensor **1700** can further include Fabry-Perot gratings FBG **1** and FBG **2**, which can be used to sense changes in pressure. Similar to the phase-shift grating structures described above with respect to FIG. **10**D, the Fabry-Perot gratings FBG **1** and FBG **2** can create a phase shift that can be tracked in a manner similar to that described above. That is, a notch can be created in the wavelength response to the Fabry-Perot gratings FBG **1** and FBG **2**, as shown and described in detail above. A point on a slope of the notch can be set and tracked, a phase shift can be detected and quantified, and the change in pressure can be determined from the quantified phase-shift, such as described in detail above.

[0181] The pressure sensor **1700** of FIG. **17** can further include a proximal coil **1708** and a distal coil **1710**. The proximal and distal coils **1708**, **1710** can provide additional flexibility to aid advancement of the pressure sensor **1700** through tortuous pathways. In one example, the proximal and distal coils **1708**, **1710** can be affixed together via a mechanical joint **1712**, e.g., via solder or adhesive. The FBG interferometer **1704** can, in some examples, be positioned underneath the mechanical joint **1712** to provide additional protection to the FBG interferometer **1704**.

[0182] The pressure sensor **1700** of FIG. **17** can further include a guidewire **1714** to which the FBG interferometer **1704** can be attached. In the example depicted in FIG. **17**, a portion of the guidewire can define a machined gap **1716** underneath a portion of the proximal coil **1708** and the distal coil **1710**. The machined gap **1716** can allow the optical fiber **1702** to extend longitudinally or helically along the outer surface of the guidewire **1714** and then transition underneath the proximal coil **1708** gradually into the machined gap **1716**.

[0183] The example of a pressure sensor **1700** in FIG. **17** can include a cantilevered design, which can be applied to any of the examples of standalone pressure sensors described in this disclosure. More particularly, the pressure sensor **1700** can include a cantilever tube **1718** that is disposed about a distal portion of the optical fiber **1702** within the machined gap **1716**. In addition, the pressure sensor **1700** can include a sensor tube **1720** disposed within the cantilever tube **1718** and about the distal portion of the optical fiber **1702**. To provide support to a portion of the optical fiber **1702**, the pressure sensor **1700** can also include a fiber support **1722** that is positioned between the sensor tube **1720** and a portion of the optical fiber **1702**.

[0184] Between a portion of an inner surface of the cantilever tube **1718** and an outer surface of the sensor tube **1720**, the pressure sensor **1700** can define a space **1724**, thereby providing a double-walled housing construction. The double-walled housing construction and the space **1724** can allow the outer surface of the sensor tube **1720** to be mounted to the guidewire **1714** while isolating the FBG interferometer **1704** from motion of the guidewire **1714** and contact with the proximal coil **1708**.

[0185] The FBG interferometer **1704** can also define cavity **1726**, e.g., filled with air, laterally below the sensor membrane **1706** and a portion of the optical fiber **1702** and within the region defined by the sensor tube **1720**. The sensor membrane **1706** and the cavity **1726** can concentrate a stress in the area between the Fabry-Perot gratings FBG **1** and FBG **2**, which can enhance the sensitivity of the pressure sensor **1700**.

[0186] FIG. **18** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure. The example of a pressure sensor depicted in FIG. **18** can provide an example of an integrated pressure sensor that can use one or more Fabry-Perot grating arrangements.

[0187] FIG. **18** is an example of a perspective cross-sectional view of an optical fiber pressure sensor **1800** that can include an optical fiber **1802** that can be configured to transmit one or more optical sensing signals and a temperature compensated Fiber Bragg Grating (FBG) interferometer **1804** in optical communication with the optical fiber **1802**. The FBG interferometer **1804** can be configured to receive pressure, e.g., from pressure waves, and to modulate, in response to the received pressure, the optical sensing signal. The pressure sensor **1800** can include a sensor membrane **1806** that can be in physical communication with the FBG interferometer **1804**. The sensor membrane **1806** can be configured to transmit the pressure to the FBG interferometer **1804**.

[0188] The pressure sensor **1800** of FIG. **18** can further include a proximal coil **1808** and a distal coil **1810**. The proximal and distal coils **1808**, **1810** can provide additional flexibility to aid advancement of the pressure sensor **1800** through tortuous pathways. In one example, the proximal and distal coils **1808**, **1810** can be affixed together via a mechanical joint **1812**, e.g., via solder or adhesive. The FBG interferometer **1804** can, in some examples, be positioned underneath the mechanical joint **1812** to provide additional protection to the FBG interferometer **1804**.

[0189] The pressure sensor **1800** of FIG. **18** can further include a guidewire **1814** to which the FBG interferometer **1804** can be attached. In the example depicted in FIG. **18**, a portion of the guidewire **1814** can define a machined gap **1816** underneath a portion of the proximal coil **1808** and the distal coil **1810**. The machined gap **1816** can allow the optical fiber **1802** to extend longitudinally or helically along the outer surface of the guidewire **1814** and then transition underneath the proximal coil **1808** gradually into the machined gap **1816**.

[0190] The example of a pressure sensor **1800** in FIG. **18** can include a capillary tube design. More particularly, the pressure sensor **1800** can include a capillary tube **1818** to support a portion of the optical fiber **1802**. The capillary tube **1818** can be disposed about a distal portion of the optical fiber **1802** within the machined gap **1816**.

[0191] As seen in FIG. **18**, a portion **1817** of the optical fiber **1802** can extend beyond a distal end of the capillary tube **1818** and over a cavity **1820**, e.g., filled with air, that is laterally below the portion of the optical fiber **1802** that extends beyond the distal end of the capillary tube **1818**. The example of a pressure sensor **1800** of FIG. **18** can include at least three FBGs (e.g., FBGs **1**-**3**.) FBG **1** can be configured to be independent of pressure and can be used for temperature measurement, such as to provide a temperature compensated optical fiber pressure sensor, such as described above with respect to FIG. **3** and FIG. **4**A.

[0192] FBGs **2** and **3** can form a phase-shift FBG structure. The surface area of the membrane **1806** can concentrate a change in pressure and can focus a mechanical response to the change in pressure at the phase-shift region between FBG **2** and FBG **3**. This focused mechanical response can enhance the sensitivity of the pressure sensor **1800**. The mechanical forces acting upon the phase-shift region between FBG **2** and FBG **3** can concentrate a stress in the phase-shift region. The concentrated stress in the phase-shift region can change the refractive index of the optical fiber **1802**, which, in turn, alters the phase relationship between FBG **2** and FBG **3**. The change in phase-shift between FBG **2** and FBG **3** can be detected and quantified, and the change in pressure can be determined from the quantified phase-shift.

[0193] As seen in FIG. **18**, the sensor membrane **1806** can be disposed about the guidewire **1814**, the capillary tube **1818**, and the portion of the optical fiber that extends beyond the distal end of the capillary tube **1818**.

[0194] FIG. **19** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure. FIG. **19** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure. The example of a pressure sensor **1900** depicted in FIG. **19** can provide an example standalone pressure sensor that can use one or more Fabry-Perot grating arrangements.

[0195] FIG. **19** is an example of a perspective cross-sectional view of an optical fiber pressure sensor **1900** that can include an optical fiber **1902** that can be configured to transmit one or more optical sensing signals and a temperature compensated Fiber Bragg Grating (FBG) interferometer **1904** in optical communication with the optical fiber **1902**. The FBG interferometer **1904** can be configured to receive pressure, e.g., from pressure waves, and to modulate, in response to the received pressure, the optical sensing signal.

[0196] The example of a pressure sensor **1900** of FIG. **19** can include four FBGs (e.g., FBGs **1**-**4**.) FBGs **3** and **4** can form a phase-shifted FBG structure, such as for sensing temperature. The change in phase-shift between FBG **3** and FBG **4** can be detected and quantified, and the change in temperature can be determined from the quantified phase-shift, such as described above.

[0197] The pressure sensor **1900** can further include Fabry-Perot gratings FBG **1** and FBG **2**, which can be used to sense changes in pressure. Similar to the phase-shift grating structures described above with respect to FIG. **10**D, the Fabry-Perot gratings FBG **1** and FBG **2** can create a phase shift that can be tracked in a manner similar to that described above. That is, a notch can be created in the wavelength response to the Fabry-Perot gratings FBG **1** and FBG **2**, as shown and described in detail above. A point on a slope of the notch can be set and tracked, a phase shift can be detected and quantified, and the change in pressure can be determined from the quantified phase-shift, such as described in detail above.

[0198] The pressure sensor **1900** of FIG. **19** can further include a proximal coil **1906**, a distal coil **1908**, and a guidewire **1910**. The proximal and distal coils **1906**, **1908** can provide additional flexibility to aid advancement of the pressure sensor **1900** through tortuous pathways.

[0199] The pressure sensor **1900** of FIG. **19** can further include a tubular housing **1912** that can be disposed about the guidewire **1912** between the proximal and distal coils **1906**, **1908**. In one example, the proximal and distal coils **1906**, **1908** can be affixed to the housing **1912** via mechanical joints **1914**A, **1914**B, e.g., via solder or adhesive. The housing **1912** can be affixed to the guidewire **1910** via a mechanical joint **1915**.

[0200] In addition, the pressure sensor **1900** can include a sensor tube **1916** disposed within the housing **1912** and disposed about a distal portion of the optical fiber **1902**. More particularly, the sensor tube **1916** can be positioned within an area machined out of a portion of the outer wall **1918** of the housing **1912**. To provide support to the optical fiber **1902**, a fiber support **1920** can be disposed about the optical fiber **1902** between the sensor tube **1916** and the optical fiber **1902**.

[0201] To allow the received pressure to reach the optical fiber **1902**, a portion of the sensor tube **1916** can be removed in order to define a sensor window **1922**. The sensor window **1922** can be covered with the sensor membrane **1924**.

[0202] The example of a pressure sensor **1900** of FIG. **19** can include four FBGs (e.g., FBGs **1**-**4**). FBGs **3** and **4** can form a phase-shifted FBG structure, such as for sensing temperature. The change in phase-shift between FBG **3** and FBG **4** can be detected and quantified, and the change in temperature can be determined from the quantified phase-shift, such as described above.

[0203] The pressure sensor **1900** can further include Fabry-Perot gratings FBG **1** and FBG **2**, which can be used to sense changes in pressure. The Fabry-Perot gratings FBG **1** and FBG **2** can create a phase shift that can be tracked in a manner similar to that described above. That is, a notch can be created in the wavelength response to the Fabry-Perot gratings FBG **1** and FBG **2**, as shown and described in detail above. A point on a slope of the notch can be set and tracked, a phase shift can be detected and quantified, and the change in pressure can be determined from the quantified phase-shift, such as described in detail above.

[0204] The pressure sensor **1900** can define a cavity **1926**, e.g., filled with air, laterally below the sensor membrane **1924** and the optical fiber **1902**. The sensor membrane **1924** and the cavity **1926** can concentrate a stress in the area between the Fabry-Perot gratings FBG **1** and FBG **2**, which can enhance the sensitivity of the pressure sensor **1900**.

[0205] FIG. **20** depicts another example of a pressure sensor that can be used to implement various techniques of this disclosure. The example of a pressure sensor **2000** depicted in FIG. **20** can provide an example standalone pressure sensor that can use one or more Fabry-Perot grating arrangements.

[0206] FIG. **20** is an example of a perspective cross-sectional view of an optical fiber pressure sensor **2000** that can include an optical fiber **2002** that can be configured to transmit one or more optical sensing signals and a temperature compensated Fiber Bragg Grating (FBG) interferometer **2004** in optical communication with the optical fiber **2002**. The FBG interferometer **2004** can be configured to receive pressure, e.g., from pressure waves, and to modulate, in response to the received pressure, the optical sensing signal.

[0207] The example of a pressure sensor **2000** of FIG. **20** can include four FBGs (e.g., FBGs **1-4**.) FBGs **3** and **4** can form a phase-shifted FBG structure, such as for sensing temperature. The change in phase-shift between FBG **3** and FBG **4** can be detected and quantified, and the change in temperature can be determined from the quantified phase-shift, such as described above.

[0208] The pressure sensor **2000** can further include Fabry-Perot gratings FBG **1** and FBG **2**, which can be used to sense changes in pressure. Similar to the phase-shift grating structures described above with respect to FIG. **10**D, the Fabry-Perot gratings FBG **1** and FBG **2** can create a phase shift that can be tracked in a manner similar to that described above. That is, a notch can be created in the wavelength response to the Fabry-Perot gratings FBG **1** and FBG **2**, as shown and described in detail above. A point on a slope of the notch can be set and tracked, a phase shift can be detected and quantified, and the change in pressure can be determined from the quantified phase-shift, such as described in detail above.

[0209] The pressure sensor **2000** of FIG. **20** can further include a proximal coil **2006**, a distal coil **2008**, and a guidewire **2010**. The proximal and distal coils **2006**, **2008** can provide additional flexibility to aid advancement of the pressure sensor **2000** through tortuous pathways. In one example, the proximal and distal coils **2006**, **2008** can be affixed together via a mechanical joint **2012**, e.g., via solder or adhesive. The FBG interferometer **2004** can, in some examples, be positioned underneath the mechanical joint **2012** to provide additional protection to the FBG interferometer **2004**.

[0210] The pressure sensor **2000** of FIG. **20** can further include a tubular housing **2014** that can be disposed about the guidewire **2010** and underneath the mechanical joint **2012**. The housing **2014** can be affixed to the guidewire **2010** via a mechanical joint **2015**. In addition, the pressure sensor **2000** can include a sensor tube **2016** disposed within the housing **2014** and disposed about a distal portion of the optical fiber **2002**. In contrast to the tubular housing of FIG. **19**, the tubular housing **2014** of FIG. **20** can define a lumen **2018** that extends longitudinally through the housing **2014**. The sensor tube **2016** of FIG. **20** can be positioned within the lumen **2018**. To provide support to the optical fiber **2002**, a fiber support **2020** can be disposed about the optical fiber **2002** between the sensor tube **2016** and the optical fiber **2002**.

[0211] To allow the received pressure to reach the optical fiber **2002**, a portion of the sensor tube **2016** can be removed in order to define a sensor window **2022**. The sensor window **2022** can be covered with a sensor membrane **2024**.

[0212] The example of a pressure sensor **2000** of FIG. **20** can include four FBGs (e.g., FBGs **1-4**). FBGs **3** and **4** can form a phase-shifted FBG structure, such as for sensing temperature. The change in phase-shift between FBG **3** and FBG **4** can be detected and quantified, and the change in temperature can be determined from the quantified phase-shift, such as described above.

[0213] The pressure sensor **2000** can further include Fabry-Perot gratings FBG **1** and FBG **2**, which can be used to sense changes in pressure. The Fabry-Perot gratings FBG **1** and FBG **2** can create a phase shift that can be tracked in a manner similar to that described above. That is, a notch can be created in the wavelength response to the Fabry-Perot gratings FBG **1** and FBG **2**, as shown and described in detail above. A point on a slope of the notch can be set and tracked, a phase shift can be detected and quantified, and the change in pressure can be determined from the quantified phase-shift, such as described in detail above.

[0214] The pressure sensor **2000** can define a cavity **2026**, e.g., filled with air, laterally below the sensor membrane **2024** and the optical fiber **2002**. The sensor membrane **2024** and the cavity **2026** can concentrate a stress in the area between the Fabry-Perot gratings FBG **1** and FBG **2**, which can enhance the sensitivity of the pressure sensor **2000**.

[0215] FIGS. **21**A-**21**D depict another example of a guidewire in combination with an optical fiber pressure sensor. FIG. **21**A is an example of a partial cutaway view illustrating a combination **2100** of a guidewire **2102** and an optical fiber **2104** attached to an optical fiber pressure sensor **2106** (FIG. **21**C).

[0216] In one example, the guidewire **2102** can be substantially similar to the guidewire shown and described in U.S. Pat. No. 5,341,818 to Abrams et al. and assigned to Abbott Cardiovascular Systems, Inc. of Santa Clara, Calif., the entire contents of which being incorporated herein by reference. The guidewire **2102** can include a proximal portion **2108** and a distal portion **2110**. The distal portion **2110** can be formed at least partially of superelastic materials. The guidewire **2102** can further include a tubular connector **2112** that can connect a distal end **2114** of the proximal portion **2108** and a proximal end **2116** of the distal portion **2110**.

[0217] The guidewire **2102** can further include a core wire **2118** having an elongated portion **2120** and a tapered portion **2122** extending distally beyond the elongated portion **2120**. In addition, the guidewire **2102** can include a proximal coil **2124** disposed about the elongated portion **2120** and a distal coil **2126** disposed about a portion of each of the elongated portion **2120** and the tapered portion **2122** and extending distally beyond the tapered portion **2122**. The proximal coil **2124** and the distal coil **2126** can be joined together via a mechanical joint **2128**, e.g., solder or adhesive. The guidewire **2102** can further include a distal plug **2130**, about which a portion of the distal coil **2126** can be wound, or a conventional solder tip. Additional information regarding the components and construction of the guidewire **2102** can be found in U.S. Pat. No. 5,341,818.

[0218] Regarding construction of the combination **2100** of the guidewire **2102** and the optical fiber **2104** attached to an optical fiber pressure sensor **2106** (FIG. **21**C), in one example, a narrow, shallow channel or groove **2132** (FIG. **21**B) can be cut into the outer wall of the components that form the guidewire **2102**, e.g., the core wire **2118** and the tubular connector **2112**. The optical fiber **2104** can be positioned within the groove **2132**. Due to the relatively small dimensions of optical fiber **2104**, the dimensions of the groove **2132** can have minimal impact on the performance of the guidewire **2102**.

[0219] The groove **2132** can extend along the length of the guidewire **2102** substantially parallel to a longitudinal axis of the guidewire **2102**. In another example, the groove **2132** can spiral about the guidewire **2102**, e.g., a helically axially extending groove. In other examples, the groove **2132** can extend along a portion of the length of the guidewire **2102** substantially parallel to a longitudinal axis of the guidewire **2102** and then the groove **2132** can spiral about another portion of the length of the guidewire **2102**, e.g., a helically axially extending groove. The pitch of the spiral can be varied along the length of the guidewire.

[0220] The groove **2132** can be fabricated using various techniques that include, but are not limited to, etching, machining, and laser ablation. In addition, the groove **2132** can be fabricated at various stages during the construction of the guidewire **2102**, e.g., before or after applying a coating to the guidewire **2102**.

[0221] The optical fiber **2104** can be bonded to the groove **2132** using various techniques. For example, the optical fiber **2104** can be bonded to the groove **2132** by applying a hot melt adhesive to the optical fiber **2104** prior to positioning the optical fiber **2104** in the groove **2132** and then subsequently applying heat.

[0222] In other examples, rather than a groove **2132** that is cut into the outer wall of the components that form the guidewire **2102**, the guidewire **2102** can define a lumen (not depicted) that extends along a portion of the length of the guidewire **2102** substantially parallel to a longitudinal axis of the guidewire **2102**. The lumen can be coaxial with the longitudinal axis of the guidewire **2102**, or the lumen can be radially offset from the longitudinal axis of the guidewire **2102**. The optical fiber **2104** can extend along the length of the guidewire **2102** through the lumen. The dimensions of the lumen can have minimal impact on the performance of the guidewire **2102**.

[0223] In another example, the guidewire **2102** can be constructed to include an annular gap (not depicted) between the proximal coil **2124** and the elongated portion **2120**. The optical fiber **2104** can then extend along the length of the elongated portion **2120** between an outer surface of the elongated portion **2120** and an inner surface of the proximal coil **2124**. The optical fiber **2104** can be wound about the elongated portion **2120**. In some examples, the optical fiber **2104** can be secured to the elongated portion **2120**, e.g., via an adhesive.

[0224] FIG. **21**B is an example of a cross-sectional view of the combination **2100** of FIG. **21**A, such as taken along section B-B of FIG. **21**A. The guidewire **2102**, e.g., a solid guidewire, can include the fabricated groove **2132**. FIG. **21**B illustrates the optical fiber **2104** positioned within the groove **2132** of the core wire **2118** of the guidewire **2102**.

[0225] FIG. **21**C is an example of a cross-sectional view of the combination **2100** of FIG. **21**A, such as taken along section E-E of FIG. **21**A. More particularly, FIG. **21**C depicts another example of a pressure sensor **2106** that can be used to implement various techniques of this disclosure.

[0226] The optical fiber pressure sensor **2106** can include the optical fiber **2104** that can be configured to transmit one or more optical sensing signals and a temperature compensated Fiber Bragg Grating (FBG) interferometer **2134** in optical communication with the optical fiber **2104**. The FBG interferometer **2134** can be configured to receive pressure, e.g., from pressure waves, and to modulate, in response to the received pressure, the optical sensing signal.

[0227] The example of a pressure sensor **2106** of FIG. **21**C can further include FBGs (not depicted) similar to those described in detail above with respect to various examples of pressure sensors, e.g., FIG. **10**D, which can be used to sense changes in pressure. The FBGs can create a phase shift that can be tracked in a manner similar to that described above.

[0228] The pressure sensor **2106** of FIG. **21**C can further include the proximal coil **2124** and the distal coil **2126**. The proximal and distal coils **2124**, **2126** can provide flexibility to aid advancement of the pressure sensor **2106** through tortuous pathways. In one example, the proximal and distal coils **2124**, **2126** can be affixed together via a mechanical joint **2136**. The FBG interferometer **2134** can, in some examples, be positioned underneath the mechanical joint **2136** to provide additional protection to the FBG interferometer **2134**.

[0229] As indicated above, the guidewire **2102** can be fabricated with a groove **2132** (FIG. **21**B) to which the optical fiber **2104** can be attached. A portion of the optical fiber **2104** can extend underneath the mechanical joint **2136**. To allow the received pressure to reach the optical fiber **2104**, a portion of the mechanical joint **2136** can be removed in order to define a sensor window, shown generally at **2138**. The sensor window **2138** can be covered with the sensor membrane **2140**.

[0230] In the example depicted in FIG. **21**C, the pressure sensor **2106** can be constructed by fabricating a small cavity **2142** in the core wire **2118** that is in communication with the groove **2132** at the distal end of the optical fiber **2104**. The cavity **2142** can, for example, be 100 microns in diameter by 100 microns in depth. The guidewire **2102** can be constructed of the superelastic material, or a different super stiff material may be substituted at this location (not depicted), for example, aluminum oxide (Al_2O_3) or Alumina ceramic which can be precision molded to define the cavity **2142** and the groove **2132**.

[0231] The pressure sensor **2106** can further include a microballoon **2144** placed into the cavity **2142**. In some examples, an adhesive (not depicted) can be placed in the cavity **2142** to secure the microballoon **2144** in place. The microballoon **2144** can be filled with a gas, sealed, and heat expanded such that, when expanded, the microballoon **2144** can fill the cavity **2142** and maintain a sealed reference chamber. If an upper surface of the microballoon **2144** is constricted during its expansion, a flat diaphragm can be achieved. The optical fiber **2104** with FBGs can be positioned in the groove **2132** and across the flat diaphragm of the microballoon **2144**.

[0232] The remaining space of the cavity **2142** and the groove **2132** can be filled with an adhesive (not depicted) such as silicone to capture the optical fiber **2104**, to attach the optical fiber **2104** to the guidewire **2102**, to attach the optical fiber **2104** to the microballoon **2144**, and to define a relatively thin silicone diaphragm in mechanical communication with the chamber defined by the microballoon **2144** where the optical fiber **2104** is embedded. As a pressure is applied, each of the silicone, the optical fiber **2104**, and the microballoon **2144** can flex due to compression of the sealed chamber. The flexing can transmit the received pressure to the FBG interferometer **2134**, which can create a responsive phase shift between FBGs (not depicted) that can be tracked in a manner similar to that described above.

[0233] FIG. **21**D is an example of a cross-sectional view of the combination **2100** of FIG. **21**A, such as taken along section A-A of FIG. **21**A. More particularly, FIG. **21**D depicts a cross-sectional view of the pressure sensor **2106** of FIG. **21**C. As seen in FIG. **21**D and as described above with respect to FIG. **21**C, the pressure sensor **2106** of FIG. **21**C can include the microballoon **2144** positioned within the cavity **2142**. The optical fiber **2104** with FBGs can be positioned in the groove **2132** and across the flat diaphragm **2146** of the microballoon **2144**.

[0234] Any of optical fiber pressure sensors described in this disclosure can be combined with the guidewire **2102** shown and described above with respect to FIG. **21**A and in U.S. Pat. No. 5,341,818. Further, the techniques of this disclosure are not limited to the use of a single sensor in combination with a guidewire, e.g., guidewire **2102**. Rather, two or more sensors, e.g., pressure sensors, can be combined with a guidewire by defining sensor regions in which each of the two or more sensors can function at a respective, unique wavelength and can be addressed accordingly by a laser matching the wavelength of the respective sensor. Each laser can be multiplexed onto the optical fiber using standard techniques, e.g., wavelength-division multiplexing (WDM), found in telecommunications systems.

[0235] In another example, the guidewire **2102** of FIG. **21**A can be combined with other sensor techniques. For example, the same guidewire can be used for both intravascular ultrasound (IVUS) imaging and pressure sensing by using the imaging sensor configurations described in U.S. Pat. No. 7,245,789 to Bates et al., and assigned to Vascular Imaging Corp, the entire contents of which being incorporate herein by reference. By way of specific example, one of the optical fibers in a 32 fiber arrangement can extend distally beyond an imaging sensor region, where an optical fiber pressure sensor, such as any of the optical fiber pressure sensors described in this disclosure, can be included that utilizes a different wavelength than that used by the imaging arrangement.

[0236] FIG. **22** depicts an example of a combination **2200** of a guidewire **2202** with an optical fiber pressure sensor **2204** and an imaging sensor **2206**, e.g., using the imaging sensor configurations described in U.S. Pat. No. 7,245,789. In particular, FIG. **22** is an example of a perspective partial cutaway view of the combination **2200**.

[0237] The guidewire **2202** is similar in construction to the guidewire **2102** described above with respect to FIG. **21**A, and as shown and described in U.S. Pat. No. 5,341,818. The guidewire **2202** can include a core wire **2208**, a proximal coil **2210**, and a distal coil **2212**.

[0238] The imaging sensor **2206** can include an optical fiber ribbon **2214** having a plurality of optical fibers, e.g., 32 optical fibers, disposed about the core wire **2208** of the guidewire **2202**, and a plurality of imaging gratings **2216** to couple light into and/or out of one or more respective optical fibers of the ribbon **2214**.

[0239] The guidewire **2202** can further include a backing **2218** disposed about the core wire **2208** and positioned between the core wire **2208** and the optical fiber ribbon **2214**. In addition, the guidewire **2202** can include a mechanical joint **2220** for joining a proximal portion **2222** of the guidewire **2202** to a distal portion **2224** of the guidewire **2202**.

[0240] In one example, the pressure sensor **2204** can be similar to the pressure sensor **2106** of FIG. **21**C. For purposes of conciseness, the pressure sensor **2204** will not be described in detail again. The pressure sensor **2204** can include a single optical fiber **2226** that extends longitudinally along the length of the guidewire **2202**, e.g., within a groove in the outer surface of the core wire **2208** and underneath the optical fiber ribbon **2214**. The pressure sensor **2204** can further include a pressure sensing window **2228** and pressure sensor membrane **2230**, as described in detail above. The pressure sensor **2204** of FIG. **22** is not limited to the design of the pressure sensor **2106** of FIG. **21**C. Rather, any of the pressure sensor configurations described in this disclosure can be applied to the combination **2200**.

[0241] In one example, an outer diameter of the guidewire **2202** can be reduced along the length of the guidewire **2202** up to the distal coil **2212** to allow the optical fiber ribbon **2214** to be disposed about the outer surface of the guidewire **2202**. By way of specific example, the outer diameter of the proximal coil **2210** can be reduced from 0.014" to 0.011" and the pressure sensor **2204** can be incorporated with the guidewire **2202** either in a surface groove or a coaxial hole of the core wire **2208**. The optical fiber ribbon **2214**, e.g., a 32 optical fiber arrangement, of the imaging sensor **2206** can then be positioned over the 0.011" outer diameter of the guidewire **2202** so that the assembly contains 33 optical fibers, for example. This configuration can separate the multiplexing requirements of the imaging sensor **2206** and the pressure sensor **2204**, and can allow the pressure sensor **2204** to operate at any wavelength, including that of the imaging sensor **2206**.

[0242] FIGS. **23**A-**23**B depict another example of a guidewire in combination with an optical fiber pressure sensor. FIG. **23**A is an example of a partial cutaway view illustrating a combination **2300** of a guidewire **2302** and an optical fiber **2304** attached to an optical fiber pressure sensor **2306** (FIG. **23**B).

[0243] The guidewire **2302** can include a proximal portion **2308** and a distal portion **2310**. The distal portion **2310** can be formed at least partially of superelastic materials. The guidewire **2302** can further include a tubular connector **2312** that can connect a distal end **2314** of the proximal portion **2308** and a proximal end **2316** of the distal portion **2310**.

[0244] The guidewire **2302** can further include a core wire **2318** having an elongated portion **2320** and a tapered portion **2322** extending distally beyond the elongated portion **2320**. In addition, the guidewire **2302** can include a proximal coil **2324** disposed about the elongated portion **2320** and the tapered portion **2322**. The guidewire **202** can also include a distal coil **2326** disposed about a portion of the tapered portion **2322** and extending distally beyond the tapered portion **2322**. The proximal coil **2324** and the distal coil **2326** can be joined together via a mechanical joint **2328**, e.g., solder or adhesive. The guidewire **2302** can further include a distal plug **2330**, about which a portion of the distal coil **2326** can be wound, or a conventional solder tip.

[0245] Regarding construction of the combination **2300** of the guidewire **2302** and the optical fiber **2304** attached to an optical fiber pressure sensor **2306**, in one example, a narrow, shallow channel or groove (not depicted) can be cut into the outer wall of the components that form the guidewire **2302**, e.g., the core wire **2318** and the tubular connector **2312**. The optical fiber **2304** can be positioned within the groove. Due to the relatively small dimensions of optical fiber **2304**, the dimensions of the groove can have minimal impact on the performance of the guidewire **2302**.

[0246] The groove can extend along the length of the guidewire **2302** substantially parallel to a longitudinal axis of the guidewire **2302**. In another example, the groove can spiral about the guidewire **2302**, e.g., a helically axially extending groove. In other examples, the groove can extend along a portion of the length of the guidewire **2302** substantially parallel to a longitudinal axis of the guidewire **2302** and then the groove can spiral about another portion of the length of the guidewire **2302**, e.g., a helically axially extending groove. The pitch of the spiral can be varied along the length of the guidewire.

[0247] The groove can be fabricated using various techniques that include, but are not limited to, etching, machining, and laser ablation. In addition, the groove can be fabricated at various stages during the construction of the guidewire **2302**, e.g., before or after applying a coating to the guidewire **2302**.

[0248] The optical fiber **2304** can be bonded to the groove using various techniques. For example, the optical fiber **2304** can be bonded to the groove by applying a hot melt adhesive to the optical fiber **2304** prior to positioning the optical fiber **2304** in the groove and then subsequently applying heat.

[0249] The guidewire **2302** can be constructed to include an annular gap, shown in FIG. **23**B at **2332**, between the proximal coil **2324** and the portions **2320**, **2322**. The optical fiber **2304** can then extend along the length of the portions **2320**, **2322** of the distal portion **2310** between an outer surface of the portions and an inner surface of the proximal coil **2324**. The optical fiber **2304** can be wound about the elongated portion **2320**. In some examples, the optical fiber **2304** can be secured to the elongated portion **2320**, e.g., via an adhesive.

[0250] The combination **2300** can further include a sleeve **2334** disposed about the core wire **2318** and underneath the mechanical joint **2328**, to receive a distal portion of the optical fiber **2304**. In one example, sleeve **2334** can be constructed of aluminum oxide (Al_2O_3), or other stiff material. The core wire **2318** can taper as it extends underneath the mechanical joint.

[0251] FIG. **23**B is an example of a partial cutaway view of a portion of the combination **2300** of FIG. **23**A. More particularly, FIG. **23**B depicts another example of a pressure sensor **2306** that can be used to implement various techniques of this disclosure.

[0252] The optical fiber pressure sensor **2306** can include the optical fiber **2304** that can be configured to transmit one or more optical sensing signals and a temperature compensated Fiber Bragg Grating (FBG) interferometer **2334** in optical communication with the optical fiber **2304**. The FBG interferometer **2334** can be configured to receive pressure, e.g., from pressure waves, and to modulate, in response to the received pressure, the optical sensing signal.

[0253] The example of a pressure sensor **2306** of FIG. **23**B can further include FBGs (not depicted) similar to those described in detail above with respect to various examples of pressure sensors, e.g., FIG. **10**D, which can be used to sense changes in pressure. The FBGs can create a phase shift that can be tracked in a manner similar to that described above.

[0254] The pressure sensor **2306** of FIG. **23**B can further include the proximal coil **2324** and the distal coil **2326**. The proximal and distal coils **2324**, **2326** can provide flexibility to aid advancement of the pressure sensor **2306** through tortuous pathways. In one example, the proximal and distal coils **2324**, **2326** can be affixed together via a mechanical joint **2328**. The FBG interferometer **2334** can, in some examples, be positioned underneath the mechanical joint **2328** to provide additional protection to the FBG interferometer **2334**.

[0255] As indicated above, the guidewire **2302** can be constructed to include an annular gap **2332** between the proximal coil **2324** and the portion **2320** to allow the optical fiber **2304** to extend along the length of the portion **2320**. The sleeve **2334** can include a lumen, groove, or pocket to receive the distal end of the optical fiber **2304**. To allow the received pressure to reach the optical fiber **2304**, a portion of the mechanical joint **2328** and the sleeve **2334** can be removed in order to define a sensor window, shown generally at **2338**. The sensor window **2338** can be covered with the sensor membrane **2340**.

[0256] In the example depicted in FIG. **23**B, the pressure sensor **2306** can be constructed by fabricating a small cavity **2342** in the core wire **2318**. The cavity **2342** can, for example, be 100 microns in diameter by 100 microns in depth. The guidewire **2302** can be constructed of the superelastic material, or a different super stiff material may be substituted at this location (not depicted), for example, Al_2O_3, or Alumina ceramic which can be precision molded to define the cavity **2342**.

[0257] The pressure sensor **2306** can further include a microballoon **2344** placed into the cavity **2342**. In some examples, an adhesive (not depicted) can be placed in the cavity **2342** to secure the microballoon **2344** in place. The microballoon **2344** can be filled with a gas, sealed, and heat expanded such that, when expanded, the microballoon **2344** can fill the cavity **2342** and maintain a sealed reference chamber. If an upper surface of the microballoon **2344** is constricted during its expansion, a flat diaphragm can be achieved. The optical fiber **2304** with FBGs can be positioned in the sleeve **2334** and across the flat diaphragm of the microballoon **2344**.

[0258] As a pressure is applied, the optical fiber **2304** and the microballoon **2344** can flex due to compression of the sealed chamber. The flexing can transmit the received pressure to the FBG interferometer **2334**, which can create a responsive phase shift between FBGs (not depicted) that can be tracked in a manner similar to that described above.

[0259] FIG. **24** shows an example of a portion of a concentric pressure sensor assembly **2400**. The concentric pressure sensor assembly **2400** can include or be coupled to an optical fiber **2402**, such as a reduced-diameter longitudinally extending central optical fiber **2402**. The concentric pressure sensor assembly **2400** can be located at or near a distal region of the optical fiber **2402**. In an example, the pressure sensor assembly **2400** can include at least one Fabry-Perot interferometer, such as in the optical fiber **2402**. The Fabry-Perot interferometer can modulate the wavelength of light in the optical fiber **2402**, such as in response to environmental pressure variations that can stretch or compress the optical fiber **2402**, e.g., longitudinally and linearly. The modulated light in the optical fiber **2402** can be used to communicate information about the environmental pressure variations at or near the distal end of the optical fiber **2402** to a proximal end of the optical fiber **2402**, such as for coupling the resulting optical signal to an optoelectronic or other optical detector, which, in turn, can be coupled to electronic or optical signal processing circuitry, such as for extracting or processing the information about the sensed environmental pressure variations.

[0260] A distal portion of the optical fiber **2402** (e.g., more distal than the one or more Fabry-Perot interferometers) can be securely captured, anchored, or affixed, such as at a hard, solid, or inelastic distal disk assembly, distal endcap, or other distal anchor **2404**, such as can be located at a distal end portion of the concentric pressure sensor assembly **2400**. The hard, solid, or inelastic material (e.g., fused silica or other suitable material) of the distal anchor **2404** can be relatively inflexible, e.g., relative to the dimensional variation of the optical fiber **2402** in response to the targeted environmental pressure variations to be measured. In an illustrative example, any dimensional variation of the distal anchor **2404** can be less than or equal to 1/20, 1/100, or 1/1000 of any dimensional variation of a pressure-sensing portion of the optical fiber **2402** measured in response to the targeted environmental pressure variations, such as the pressure variations that can be present in a percutaneous in vivo intravascular human blood pressure sensing application.

[0261] The tubular or other distal anchor **2404** can be attached to a hard, solid, or inelastic (e.g., fused silica) tubular or other housing **2406**, such as by a soft, flexible, elastic, or compliant gasket **2408** that can be located therebetween. A first sensing region **2410** of the optical fiber **2402** can be securely captured, anchored, or affixed, to the housing **2406**, such as via a tubular or other attachment (e.g., hardened epoxy or other adhesive) region **2412**. A second sensing region **2414** of the optical fiber **2402** can be located within the housing **2406**, such as suspended (e.g., freely or within a compliant material) between the encapsulator or attachment region **2412** and the hard distal anchor **2404**. The suspended portion of the optical fiber **2402** can be installed or securely held longitudinally under tension. This can permit both positive and negative direction longitudinal displacement variations in the suspended portion of the optical fiber **2402**, which, in turn, can permit sensing of both positive and negative environmental pressure variations, as explained herein.

[0262] The gasket **2408** material (e.g., medical grade silicone) can be relatively more flexible, soft, elastic, or compliant than the housing **2406** and than the distal anchor **2404**, such as to allow longitudinal dimensional variation of gasket **2408** and the suspended second sensing region **2414** of the optical fiber **2402** in response to the targeted environmental pressure variations to be measured, such as the pressure variations that can be present in a percutaneous in vivo intravascular human blood pressure sensing application. The first sensing region **2410** can be securely fixed to the hard housing **2406** by the encapsulator or attachment region **2412**, while the second sensing region **2414** can be suspended within the hard housing **2406** and subject to longitudinal dimensional variation (along with longitudinal dimensional variation of the compliant gasket **2408**). Therefore, the first sensing region **2410** can be shielded from or made insensitive to environmental pressure variations, but sensitive to environmental temperature variations, while the second sensing region **2414** can be sensitive to both environmental pressure and temperature variations. In this way, light modulation in the first sensing region **2410** due to temperature variations can be measured and used to compensate for or null-out the light modulation effect of similar temperature variations experienced by the second sensing region **2414** that is being used to measure environmental pressure variations. In an illustrative example, the first sensing region **2410** can include a first Fabry-Perot interferometer, and the second sensing region **2414** can include a second Fabry-Perot interferometer. These respective interferometers can be written with different wavelengths. This can permit each interferometer to be individually separately addressed by selecting a corresponding wavelength of light to provide to the proximal end of the optical fiber **2402** to perform the selective individual addressing of the interferometers.

[0263] FIG. **24** can be conceptualized as an arrangement in which at least one optical fiber sensing region can be suspended between two anchors (e.g., hard tubes **2404**, **2406**) that can be separated from each other by a compliant region (e.g., gasket **2408**) that can allow the anchoring tubes **2404**, **2406** (and hence the suspended portion of the optical fiber **2402**) to experience longitudinal displacement in response to environmental pressure variations. Based on finite element modeling (FEM) simulation analysis and experimental laboratory data obtained from prototypes, corresponding to the arrangement illustrated in FIG. **24**, a pressure sensitivity can be obtained that can be at least 100 to 150 times the pressure sensitivity of an optical fiber without such arrangement of hard tubes **2404**, **2406** separated from each other by the compliant gasket **2408**.

[0264] In an illustrative example, the entire pressure sensor assembly **2400** can be less than or equal to 1.5 millimeters in length, such as less than or equal to 1.0 millimeter in length. The pressure sensor assembly **2400** can have an outer diameter that can be less than or equal to 125 micrometers. For comparison, 125 micrometers is the outer diameter of a typical single standard optical fiber as used in telecommunications. The tubular housing **2406** can have an inner lumen diameter of about 50 micrometers. In an example, the entire pressure sensor assembly **2400** can be conveniently incorporated within a percutaneous or other guidewire, such as can be used for guiding an intravascular device (e.g., a stent, such as a coronary stent) to a desired location within a blood vessel. For example, the entire pressure sensor assembly **2400** can be included within a solder or other joint of such a guidewire, such as between spring coils forming a body of the guidewire. Using fused silica or other glass components for all or portions of the tubular housing **2406** or the fused silica distal anchor **2404** can provide components that can provide a good matching of the temperature coefficient of expansion of these materials to the temperature coefficient of expansion of the material of the optical fiber **2402**.

[0265] The arrangement shown in the illustrative example of FIG. **24** can advantageously be durable, can be easy to make, can perform well such as in detecting and amplifying an environmental pressure variation, or can consistently be made in a small form factor.

[0266] FIG. **25** shows an example of the pressure sensor assembly **2400** as it can be prefinished and included or otherwise incorporated into a percutaneous intravascular guidewire assembly **2500**. The guidewire assembly **2500** can include a core guidewire **2502**, a flexible proximal spring coil region **2504** and a flexible distal spring coil region **2506** that can terminate at a rounded and atraumatic distal tip. A generally cylindrical or other connector block **2508** can be included between and interconnecting the proximal spring coil region **2504** and the distal spring coil region **2506**. The connector block **2508** can include a reduced diameter proximal end seat region **2510** and a reduced diameter distal end seat region **2512**, about which windings of the flexible proximal spring coil region **2504** and a flexible distal spring coil region **2506** can respectively be wound, such as with their outer circumferences flush with an outer circumference of a midportion of the connector block **2508** between the proximal end seat region **2510** and the reduced diameter distal end seat region **2512**. The connector block **2508** can provide a housing for the pressure sensor assembly **2400**. The optical fiber **2402** can extend proximally from the pressure sensor assembly **2400** in the connector block **2508** through the proximal spring coil region **2504**, such as to an optical connector at a proximal end of the guidewire assembly **2500**, where it can be optically coupled to optical, electronic, or optoelectronic signal generation or processing circuitry. The core guidewire **2502** of the guidewire assembly **2500** can bend or jog off of the concentric longitudinal axis of the guidewire assembly **2500**, such as at or near the connector block **2508**, if needed to allow enough room for the pressure sensor assembly **2500** to be housed within the connector block **2508** while also allowing passage of the core guidewire **2502** through the connector block **2508** in such a lateral offset arrangement.

[0267] The connector block **2508** can provide a lateral axis portal **2514** that can be located beyond a distal end region **2516** of the pressure sensor assembly **2400** such as to leave a distal end region **2516** of the pressure sensor assembly **2400** exposed to nearby environmental pressures to be measured, while providing a ceramic or other hard protective circumferential housing region that can protect the pressure sensor assembly **2400** from lateral pressure or lateral torque that may otherwise influence the pressure sensor measurement to be obtained by longitudinal spatial variations of the pressure sensor assembly **2400**.

[0268] FIG. **26** shows an example illustrating how components of the pressure sensor assembly **2400** can be integrated into or otherwise incorporated into a percutaneous intravascular guidewire assembly **2600**. FIG. **26** is similar to FIG. **25** in some respects, but in FIG. **26** the connector block **2602** can provide a concentric axially aligned longitudinal passage for the core guidewire **2502**, such that it need not bend or jog as shown in FIG. **25**. This can help preserve or utilize the mechanical properties or characteristics of the core guidewire **2502** or those of the guidewire assembly **2600**. One or more components of the pressure sensor assembly **2400** can be laterally offset from the concentric axially aligned core guidewire **2502**, such as within the connector block **2602**. The connector block **2602** can include a lateral axis portal **2514**. The distal anchor **2404** and the gasket **2408** can be located in or near the lateral axis portal **2514**, and can optionally be laterally recessed or otherwise shielded from lateral pressure or torque that may otherwise influence the pressure sensor measurement to be obtained by longitudinal spatial variations of the integrated components of the pressure sensor assembly **2400**, such as explained above with respect to FIG. **25**. The connector block **2602** can be constructed with a passage for the optical fiber **2402** sized, shaped, or otherwise configured such as to provide a first sensing region **2410** of the optical fiber **2402** that can be affixed to a housing provided by the connector block **2602**, such as explained herein. A second sensing region **2414** of the optical fiber **2402** can be suspended within a housing provided by the connector block **2602**, such as explained herein. The optical fiber **2402** can extend outward from the connector block **2602** proximally, such as through the proximal spring coil region **2504**, such as with the optical fiber **2402** extending so as to be laterally offset from a longitudinal central axis of the guidewire assembly **2600**.

[0269] FIG. **27** shows an example in which components of the pressure sensing assembly **2400** can be retrofitted to or otherwise integrated into an existing guidewire assembly **2700**, such as a RUNTHROUGH® guidewire, available from Terumo Kabushiki Kaisha, also known as Terumo Corp. The guidewire assembly **2700** can include a proximal region **2702**, that can be constructed from a first material, such as stainless steel, and a distal region **2706** that can be constructed from a second material, such as nitinol. Either or both of the proximal region **2702** and the distal region **2704** can taper inward in a direction toward the distal end of the guidewire assembly **2700**, such as in one or more tapering regions, which can be contiguous or separated by respective non-tapering regions. A distal region **2706** of the guidewire assembly **2700** can include a proximal spring coil region **2504**, a distal spring coil region **2506**, a connector block **2708** (e.g., containing components of the pressure sensor assembly **2400**, such as described herein) therebetween from which a flattened or other core guidewire can extend distally toward and connecting to an atraumatic rounded distal tip **2710**.

[0270] At least one groove **2712** can be formed on an outward circumferential surface of the guidewire assembly **2700**. The groove **2712** can extend from a proximal end or region of the guidewire assembly **2700** toward and to a distal portion of the guidewire assembly **2700** and can terminate at a proximal side of the connector block **2708**. The groove **2712** can extend along all or a portion of the length of the guidewire assembly **2700**, such as in a spiral helix or otherwise. The pitch of the helix can be fixed or multi-valued (e.g., a looser pitch (e.g., between 30 mm and 50 mm) at a proximal portion of the guidewire assembly **2700** and a tighter pitch (e.g., between 5 mm and 10 mm pitch) at the distal (e.g., over a length of about 30 centimeters) portion of the guidewire assembly **2700**). The helical arrangement can help accommodate flexing curvature in the guidewire assembly **2700** as it is introduced along tortuous vascular or other non-linear paths. A tighter pitch can be more accommodating to curvature in the guidewire assembly **2700**. The groove **2712** can carry the optical fiber **2402** therein, such as can be secured therein by an adhesive underlayer (e.g., UV-cured adhesive, hot-melt adhesive, epoxy or other two-part adhesive) or overlayer (e.g., such as any suitable overcoating used for an existing guidewire). In an example, the groove **2712** can be about 40 micrometers across and about 40 micrometers deep, and can be constructed so as to only occupy about 1/100 or less of the surface area of the guidewire assembly **2700**, thereby leaving the mechanical properties of the guidewire assembly **2700** substantially intact as though the groove **2712** were not present. For retrofitting an existing guidewire, the groove **2712** can be formed by laser-etching or other suitable process. The guidewire can additionally or alternatively formed together with the groove **2712**, such as during drawing of the guidewire body during its manufacture, such as by mechanically scoring the guidewire body or otherwise. If a portion of the guidewire body is tapered down (e.g., toward a distal end, such as using centerless or other grinding), then any grooves that were formed during the guidewire drawing, but removed by the grinding, can be replaced by a respective connecting groove that can be formed after grinding, such as by laser-etching the ground portion of the guidewire body.

[0271] FIG. **28** shows an example in which the pressure sensor assembly **2400** (e.g., as explained herein) can be located at a distal end of a guidewire assembly **2800**, e.g., more distal than the distal spring coil region **2506**, such as within or providing a rounded atraumatic distal tip. A flattened or other distal end of the core guidewire **2502** can connect to a proximal end of the housing **2406** of the pressure sensor assembly **2400**. More proximal regions of the guidewire assembly **2800** can include a proximal spring coil region **2504**, a connector block (such as a connector block **2508**, which can optionally include a second, more proximal pressure sensor as described with respect to FIG. **25**), and other elements such as shown in FIG. **25**.

[0272] The distal end pressure sensor assembly **2400** can include an anchored first sensing region **2410** and a suspended second sensing region **2414**, such as explained herein. The gasket **2408** and the distal anchor **2404** can be located within a cylindrical or other recess **2802** that can be exposed to the ambient environment about the distal end of the guidewire assembly **2800**. In an example such as shown in FIG. **28**, the recess **2802** can be cylindrical and can extend longitudinally along the central axis of the guidewire assembly **2800**, such as to face longitudinally outward from the distal end of the guidewire assembly **2800**. In an example, the distal end of the optical fiber **2402** can be attached to the anchor **2404**, and both the anchor **2404** and the gasket **2408** can be suspended within the recess **2802**, such as by tension in the optical fiber **2402** to which the anchor **2404** can be attached with the gasket **2408** captured proximal to the anchor **2404**. This can help provide pressure sensing due to longitudinal optical fiber tension variations near the distal end of the guidewire assembly **2800**, and can help isolate the effect of lateral pressure variations or torque upon the pressure sensor assembly **2400**.

[0273] Having a pressure sensor located at a guidewire distal tip can provide advantages in certain applications, such as where information about pressure distal to an occlusion may be desirable. For example, when pushing a guidewire across a chronic total vascular occlusion, it may be difficult to determine whether the distal tip is within a lumen of the blood vessel or within a subintimal layer of the blood vessel. A distal-tip pressure sensor can permit providing distal-tip pressure information that can be useful in determining the nature of such location of the distal tip of the guidewire assembly **2800**. In an example in which a distal tip pressure sensor is provided together with a more proximal pressure sensor (e.g., located between the proximal spring coil region **2504** and the distal spring coil region **2506**), a pressure differential across an occlusion can be sensed and provided to a user, such as for diagnostic or interventional (e.g., stent-placement) purposes.

[0274] FIG. **29** shows an example of a proximal region of a guidewire assembly **2900**, such as one of the various guidewire assemblies described herein, terminating at a proximal end connector **2902**. The guidewire assembly **2900** can include a helically wound optical fiber **2402** that can be located in a helical groove **2712** along the guidewire body. The proximal end connector **2902** can include separable portions: (1) a distal portion that can include a metal or other tube **2904** (also referred to as a tubular coupler) having an interior lumen diameter that can be attached to both the outer diameter of the body of the proximal region of the guidewire assembly **2900** and the outer diameter of a ceramic or other distal ferrule **2906** such that the optical fiber can extend from a periphery of the guidewire body to and through a center axis lumen of the distal ferrule **2906**; and (2) a proximal portion that can include a connector housing **2908** carrying a ceramic or other proximal ferrule **2910**, a split sleeve ferrule guide **2912**, and a distal receptacle guide **2914** that can provide a tapered portion into which a portion of the distal ferrule **2906** and the metal tube **2904** can be received. The optical fiber **2402** can terminate at a flat or dome polished (e.g., ultrapolished physical connector, "UPC") proximal end of the distal ferrule **2906**, where it can butt against and optically couple with a flat or dome polished (e.g., UPC) distal end of the proximal ferrule **2910**, which can provide a center axis lumen through which an optical fiber **2402** can extend in a proximal direction, such as to an optical, electronic, or optoelectronic signal generation or processing apparatus. While the optical fibers **2402** and **2916** can be the same diameter, in an example, the optical fiber **2402** can be a small diameter optical fiber (e.g., 25 micrometers outer diameter) and the optical fiber **2916** can be a standard sized telecommunications optical fiber (e.g., 125 micrometers outer diameter), such as with the mode field diameter (MFD) of the optical fiber **2402** being less than or equal to the MFD of the optical fiber **2916**. When the proximal end of the guidewire terminating in connector portion **2902** is detached, other components can be easily slipped over the guidewire.

[0275] Using various techniques described above, changes in ambient pressure can be detected by measuring the wavelength change, e.g., quantified change in phase-shift, by an FBG sensor within a housing, e.g., housing **308** of FIG. **3**. As described above with respect to FIGS. **4A-4C** and FIG. **6A**, the change in phase-shift can be quantified by locking a laser at a position on a slope of the transmission notch of the resonant feature, tracking a particular optical power level in the resonant feature, and adjusting the bias current of the laser which, in turn, subtly changes the wavelength to maintain this "locked" relationship.

[0276] These techniques can produce satisfactory results when the optical insertion loss is constant. In some example implementations, however, the overall insertion loss of the pressure sensor and/or system can change during the measurement, e.g., kinking in the optical fiber. As shown and described below with respect to FIG. **30**, a change in the optical insertion loss can lead to an artificial shift in the tracking wavelength, and thus an offset error in the pressure reading, if the optical locking level or threshold is not adjusted accordingly.

[0277] FIG. **30** depicts a conceptual response diagram illustrating the effect of an uncorrected locking level on a locking wavelength. In FIG. **30**, where the x-axis represents wavelength and the y-axis represents the intensity of the reflected light, a transmission notch **3000** is shown within a reflection band **3002**, and a reduced reflection band **3004**, which is caused by insertion loss. An initial locking level, or optical threshold, **3006** is depicted, which corresponds to a wavelength of about 1550.85 nm and a reflection intensity of 50%.

[0278] If insertion loss is introduced, which results in the reduced reflection band **3004**, then the locking level may move up or down the slope of the reduced reflection band **3004** in order to maintain its locking level, e.g., 50%, despite the fact that the transmission notch **3004** has not moved. If the insertion loss increases (optical power decreases), then the shift can be to a higher, incorrect locking wavelength because the locking circuit climbs the slope of the reduced reflection band **3004** to maintain the set optical level, as shown at **3008**. If the insertion loss decreases (optical power increases)(not depicted in FIG. **30**), then the shift can be to a lower, incorrect locking wavelength because the locking circuit moves down the slope of the reduced reflection band **3004** to maintain the set optical power level. Either of these conditions can lead to a significant drift in the apparent pressure level even if there has been no phase-shift change in the FBG filter.

[0279] As described in more detail below, using various techniques of this disclosure, the locking level **3006** can be corrected for insertion loss, resulting in a corrected locking level **3010**. In accordance with this disclosure, a small dither signal can be added to the wavelength of the laser at, for example, a frequency outside those associated with the pressure sensing. Then, the AC component, which is the change in the optical signal reflected from the pressure sensor back to the optical detector, e.g., optical detector **608** of FIG. **6**A, can be extracted from the optical signal via an electronic circuit associated with the optical detector. The magnitude of the AC component can then be used to make any adjustments to the locking level to null out any offset errors.

[0280] FIG. **31** depicts the conceptual response diagram of FIG. **30** compensated for optical insertion loss in an optical pressure sensor using various techniques of this disclosure. In FIG. **31**, where the x-axis represents wavelength and the y-axis represents the intensity of the reflected light, a transmission notch **3000** is shown within a reflection band **3002**, and a reduced reflection band **3004**, which is caused by insertion loss.

[0281] Two AC components **3012**, **3014** are depicted in FIG. **31**, where the AC component **3012** depicts a magnitude of the AC component with no excess loss and where the AC component **3014** depicts a magnitude of the AC component with excess loss. Thus, the magnitude of the AC component can change with insertion loss.

[0282] As indicated above, a small dither signal **3016** can be added to the wavelength of the laser. Then, an AC component can be extracted from the optical signal via an electronic circuit associated with the optical detector. As can be seen in FIG. **31**, the amplitude of the AC components **3012**, **3014** can vary in proportion to the overall signal level as long as the amount of wavelength dither is held constant. That is, if the wavelength range of the dither **3016** is held constant, the magnitude of the AC component can scale directly with the optical insertion loss.

[0283] By comparing a current value of the AC component, e.g., AC component **3014**, to an initial value of the AC component, e.g., AC component **3012**, the controller **602** (FIG. **6**A) can determine whether the optical insertion loss has increased or decreased. The current value of the AC component can be fed back to the optical locking circuit of FIG. **6**A, a portion of which is described below with respect to FIG. **33**. Then, because the AC component is reduced in proportion to the change in insertion loss, the controller **602** of FIG. **6**A can adjust the optical locking level accordingly to maintain the correct locking wavelength.

[0284] In some examples, a frequency and amplitude of the wavelength dither **3016** can be selected so as to be compatible with the pressure measurements. For example, for the dither frequency, a value can be selected that is higher than the necessary bandwidth for pressure sensing. Assuming, for example, that the pressure bandwidth is between 0-25 Hz, then it might be desirable to select a frequency for the wavelength dither at least five times higher than the pressure bandwidth.

[0285] FIG. **32** is a flow diagram illustrating an example of a method **3200** for compensating for optical insertion loss in an optical pressure sensor using various techniques of this disclosure. The controller **602** of FIG. **6**A can establish, or determine, an optical locking level with no excess insertion loss (**3202**), e.g., initial locking level **3006** of FIG. **31**, and establish, or determine, an initial amplitude of a dither signal (**3204**), e.g., the AC component **3012** of FIG. **31**, by extracting the dither signal from the optical signal reflected from the pressure sensor and measuring its amplitude. The controller **602** can measure a new amplitude of the dither signal (**3206**), e.g., the AC component **3014** and compare the new amplitude to the initial amplitude (**3208**). If the insertion loss has changed (“YES” branch of **3210**), as determined by the comparison at **3208**, then the controller **602** can control either the laser drive current control **614** of FIG. **6**A or the locking set point value **612** of FIG. **6**A to adjust the locking level to a new value (**3212**), e.g., if the AC component decreases then the locking level is reduced by the appropriate amount. If the insertion loss has not changed (“NO” branch of **3210**), as determined by the comparison at **3208**, then the controller **602** can continue to measure the new amplitude of the dither signal at **3206**.

[0286] FIG. **33** is a block diagram of an example of a portion of the laser tracking system of FIG. **6**A for compensating for optical insertion loss in an optical pressure sensor using various techniques of this disclosure, in accordance with this disclosure. An AC dither generator **3312** generates a dither signal that is summed together with the laser control current via summer **3314** and passed to the laser current drive circuit **614**. The laser current drive circuit **614** generates a drive current for laser **604** of FIG. **6**A.

[0287] An optical signal reflected back from the pressure sensor, e.g., pressure sensor **300** of FIG. **3**, is detected by the optical detector **608**, amplified by electrical amplifier **3300**, and filtered by a low pass filter **3302**, e.g., frequencies of about 0-25 Hz, and a high pass filter **3304**, e.g., frequencies greater than 25 Hz. The low pass filter **3302** passes the DC level to a locking comparator **3306** and the high pass filter **3304** passes the high pass filtered signal, or AC component, to the controller **602**, which measures the amplitude of the dither signal (**3308**), or AC component, and calculates the optical locking level (**3310**), e.g., if the AC component decreases then the locking level is reduced to the appropriate value. The controller **602** passes the calculated optical locking level to the locking comparator **3306**, which compares the DC level and the calculated optical locking level. The laser current drive circuit **614** or the locking set point **612** can be adjusted based on the comparison. In this manner, a constant center wavelength is maintained.

[0288] In one example implementation, the frequency of the dither **3016** of FIG. **31** can be selected in order to design a low-pass filter **3302** that can reduce the residual AC dither component in the electrical path to the locking circuit controlled by the laser current drive circuit **614**. This may be desirable in order to prevent the locking circuit from chasing the locking level at the frequency of the dither. It may be desirable for the locking circuit to see the average or DC level of the optical locking level.

[0289] There are many ways to filter the optical signal and only one example is presented in this disclosure. Other filtering techniques or techniques for suppressing the AC component could be employed and are considered within the scope of this disclosure.

[0290] In order to ensure that the laser is able to respond to the dither frequency chosen without any reduction in the actual wavelength shift desired, there may be factors to consider in selecting a dither frequency. For example, it has been found that the design of the laser submount has an effect on the frequency at which the laser can dither the laser.

[0291] Typical dither frequencies can range from around 100 Hz to 1000 Hz before the response starts to diminish. In one example implementation, it may be desirable to select a dither frequency between about 300 Hz and about 10400 Hz.

[0292] The dither magnitude can be selected to have an appropriate scale to give a detectable AC component, e.g., around ±10% of the overall DC signal level. In this example, if the maximum optical power level is assumed to be about 1000 μW and the slope is assumed to be about 50 μW/pm, then it may be desirable to shift the wavelength of the laser by the equivalent of about ±2 pm (±1000 μW). If the laser is assumed to have a wavelength coefficient of about 5 pm/mA, then this would equate to a bias current dither of about ±0.4 mA. These numbers are given for purposes of illustration only and could be adjusted within sensible limits.

[0293] To summarize, with respect to FIGS. **31-33**, this disclosure describes, among other things, the following techniques: compensating for changes in optical insertion loss of the pressure sensor that would otherwise be seen as large drifts in the apparent measured pressure; calculating and adjusting an optical locking level to achieve compensation of changes in optical insertion loss by wavelength dithering of the tracking laser; applying wavelength dither to a tracking laser to generate a signal with amplitude proportional to optical insertion loss; and applying feedback to an optical locking level to compensate optical insertion loss.

[0294] It should be noted that the dither techniques described above can be used in a similar manner to track the insertion loss of an intravascular ultrasound (IVUS) imaging device and to make adjustments to the optical locking levels. It may also be desirable to make dynamic adjustments to a sensitivity correction matrix for the imaging elements in a receive mode. The quality of imaging can be improved when the sensitivity of the elements are balanced in the reconstruction matrix to reduce side-lobe levels.

[0295] A first order calibration of the receive sensitivity of the elements can be made by measuring the AC component from the wavelength dither as this indicates the slope of the sensing element. The expected receive ultrasound signal is proportional to the ultrasound energy imparted on the element (this is converted to a change in the optical cavity length or phase-shift) multiplied by the slope of the cavity. Therefore, by knowing the slope from the dither, an expected signal sensitivity from the element can be calculated.

[0296] In the case of IVUS, the relationship of the frequencies is reversed, where the dither frequency is well below the ultrasound frequencies and is filtered out by the ultrasound electrical circuits.

[0297] To summarize, with respect to IVUS imaging devices, this disclosure describes, among other things, the following techniques: dynamically adjusting optical locking levels; dynamically adjusting an element calibration matrix to improve image reconstruction; and calibrating receive sensitivity of elements based on dither slope measurements. Many of the techniques described in this disclosure are applicable to intravascular imaging devices, such as those described in Bates & Vardi U.S. Pat. No. 7,245,789, U.S. Pat. No. 7,447,388, U.S. Pat. No. 7,660,492, U.S. Pat. No. 8,059,923, U.S. Pat. Pub. No. US-2012-0108943-A1, and U.S. Provisional Patent Application No. 61/783,716, titled "Optical Fiber Ribbon Imaging Guidewire and Methods" to Tasker et al. and filed on Mar. 14, 2013, each of which is hereby incorporated by reference herein in its entirety.

[0298] Turning to another aspect, in any optical system with highly coherent light sources, e.g., a narrow linewidth laser, there is a possibility that any unintended reflections, even very weak ones, can form a resonant optical cavity within the device. The cavity can exhibit a strong frequency component that depends on the optical path length of the cavity (in this case the length of optical fiber between reflection points). The frequency of the cavity is given by:

$$\Delta v = \frac{C}{2L}$$

where Δv=frequency separation of maxima (Hz), C=speed of light, and L=optical path length (Length×refractive index). The longer the cavity, the more closely spaced the ripples in the frequency and wavelength domains.

[0299] A large amount of optical energy can be circulated within the pressure sensing device and, under certain conditions, can form undesirable optical resonances with other elements of the system. The undesirable resonances can be formed between any two points of optical reflection. For instance, the undesirable resonances can be formed between the FBGs and a system connector, or the FBGs and a pressure wire connector. In accordance with this disclosure and as described in more detail below with respect to FIGS. **34-37**, these undesirable resonances can be averaged out using dither techniques, thereby reducing their overall effect on the pressure measurements.

[0300] FIG. **34** depicts a conceptual response diagram illustrating undesirable optical resonances caused by additional reflection in an optical system. In FIG. **34**, where the x-axis represents wavelength and the y-axis represents the intensity of the reflected light, a transmission notch **3400** is shown within a reflection band **3402**. The undesirable optical resonances are shown as ripples **3404** overlaid on the fundamental response. In this example the undesirable reflection point is at a distance of about 70 mm from the FBGs.

[0301] In an example of a pressure sensing device, there may be an optical connector to the system about two meters from the FBG filters that is a possible source of reflections. The calculated expected wavelength of the ripple caused by a reflection at two meters is approximately 0.4 pm (at 1550 nm). There is a possibility that the locking system can become confused by these ripples **3404** and hop between them, which appears as a sudden jump in the apparent pressure reading, e.g., 10 mm/Hg, shown and described below with respect to FIG. **35**. In the context of pressure sensing, such a jump is unwanted and likely unacceptable due to the need for accurate pressure measurements.

[0302] FIG. **35** depicts the conceptual response diagram of FIG. **34** further illustrating undesirable locking circuit wavelength hopping. FIG. **35** shows a calculated response for a weak reflection at **70** mm (a non-limiting example for purposes of illustration only) and how the locking circuit can become confused and shift to a different wavelength. More particularly, the locking circuit can become confused because the optical locking level **3504** can intersect both the fundamental response **3402** (at point **3506**) and a ripple **3404** (at point **3508**), resulting in two possible optical locking wavelengths. As a result of the ripple **3404**, the desired optical locking wavelength at **3500** can jump to a higher optical locking wavelength **3502**. Assuming that the sensor has a pressure-to-wavelength coefficient of around 1 pm for 25 mm/Hg and that the 2 m cavity has a ripple period of **0.4** pm, then the apparent shift is approximately 10 mm/Hg, which is highly undesirable.

[0303] In accordance with this disclosure and as described in more detail below with respect to FIG. **36**, the optical dither techniques described above can be used to average through these ripples **3404** and to reduce or eliminate their effects on determining an optical locking wavelength.

[0304] FIG. **36** depicts the conceptual response diagram of FIG. **35** compensated for optical cavity noise using various techniques of this disclosure. In accordance with this disclosure, optical wavelength dither (described above) can be used to sweep or average through a number of the ripple periods. Examples of lower and upper bounds of the dither optical wavelength are depicted at **3600**, **3602**, respectively. In the example shown in FIG. **36**, within the lower and upper wavelength bounds **3600**, **3602** are four ripples **3404** that can be averaged. Less or more ripples can be averaged.

[0305] When the laser wavelength is dithered, e.g., at a frequency at least five times the bandwidth of the pressure signal, the high frequency AC component can be extracted from the optical signal by filtering, similar to what was described above with respect to the insertion loss compensation techniques and as depicted in FIG. **33**. If the pressure signal has a bandwidth of about 0-25 Hz, then the dither frequency is at least 125 Hz, for example. In other examples, the dither frequency is about 300-400 Hz.

[0306] Once the high frequency AC component is extracted, then the controller **602** of FIG. **6** can average the AC component over the region of interest, e.g., over four ripples **3404** as in FIG. **36**. The dithering occurs at a faster rate than the rate at which the ripples **3404** move side to side during the measurement. As a result, the controller **602** can average through the ripples **3404**, thereby removing the optical cavity noise. The controller **602** can then determine an optical locking level and wavelength without becoming confused and jumping to an incorrect optical locking wavelength.

[0307] The amplitude and frequency requirements of the dither wavelength can be made to complement the insertion loss compensation (described above), e.g., a frequency of about 300-400 Hz. The amplitude of the wavelength dither can be calculated based on the wavelength separation of the undesirable ripples. In one example, it may be desirable to dither by a wavelength amount that would encompass a sufficient number of ripples to give satisfactory averaging. If the ripples are more closely spaced, then the controller **602** can control generation of a relatively smaller amount of dither than if the ripples were more widely spaced to achieve the same amount of averaging. Take, for example, a two meter long distance between the reflection points, the calculated wavelength of the ripple caused by a reflection at two meters is approximately 0.4 pm (at 1550 nm), then it may be desirable to dither the wavelength of the laser by 5 ripple periods to give satisfactory averaging. The wavelength of the laser can be dithered by a total of **2** pm (0.4 pm×5 ripples). This corresponds to a dither in the laser current of around 0.4 mA, where a typical laser is 5 pm/mA.

[0308] In one example implementation, the same dither frequency and electrical filtering used for the insertion loss compensation techniques described above can be used to compensate for the optical cavity noise to allow the usual detection of the pressure readings in the 0-25 Hz bandwidth. In some example implementations, the low frequencies, e.g., 0-25 Hz, that correspond to the pressure signals can be used to control the locking circuit in order to reduce the confusion presented by individual ripples. In one example, the electrical filter circuits can be used to present the average optical detector value to the locking circuits, thus reducing the discrete step nature of the individual ripples.

[0309] FIG. **37** depicts a flow diagram illustrating an example of a method **3700** for compensating for optical cavity noise in an optical pressure sensor using various techniques of this disclosure. In FIG. **37**, the controller **602** of FIG. **6** can control the laser **604** to generate a dither signal at a frequency outside of the range associated with a pressure signal (**3702**). For example, for a pressure signal having a bandwidth of about 0-25 Hz, the dither frequency can be at least 125 Hz. In one specific example, the dither frequency can be about 300-400 Hz. Next, the optical detector **608** of FIG. **6**A can receive the reflected optical signal from the pressure sensor (**3704**). A low pass filter, e.g., filter **3302** of FIG. **33**, can remove or suppress the AC component at the dither signal frequency (**3706**). Then, the controller **602** can determine a low frequency value, e.g., the average locking level in the low frequency band (0-25 Hz), over the specified region of interest of the signal, e.g., over four ripples (**3708**). Finally, the controller **602** can determine a noise compensated optical locking wavelength based on the determined average low frequency value (**3710**).

[0310] Using the one or more techniques such as disclosed above, the present applicant has described an optical pressure sensing guidewire suitable for delivery within a body lumen of a patient, e.g., for diagnostic assessment of coronary obstructions. This can advantageously optionally provide temperature compensation for sensing pressure within a body lumen. In addition, the present subject matter can advantageously mechanically enhance the sensitivity of the fiber to pressure, such as with an extrinsic arrangement. Further, the present subject matter can utilize Fiber Bragg Gratings in the miniaturized optical fiber thereby resulting in a cost effective and manufacturable design.

[0311] Each of these non-limiting examples described above can stand on its own, or can be combined in various permutations or combinations with one or more of the other examples.

[0312] The above detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show, by way of illustration, specific embodiments in which the invention can be practiced. These embodiments are also referred to herein as "examples." Such examples can include elements in addition to those shown or described. However, the present inventors also contemplate examples in which only those elements shown or described are provided. Moreover, the present inventors also contemplate examples using any combination or permutation of those elements shown or described (or one or more aspects thereof), either with respect to a particular example (or one or more aspects thereof), or with respect to other examples (or one or more aspects thereof) shown or described herein.

[0313] In the event of inconsistent usages between this document and any documents so incorporated by reference, the usage in this document controls.

[0314] In this document, the terms "a" or "an" are used, as is common in patent documents, to include one or more than one, independent of any other instances or usages of "at least one" or "one or more." In this document, the term "or" is used to refer to a nonexclusive or, such that "A or B" includes "A but not B," "B but not A," and "A and B," unless otherwise indicated. In this document, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Also, in the following claims, the terms "including" and "comprising" are open-ended, that is, a system, device, article, composition, formulation, or process that includes elements in addition to those listed after such a term in a claim are still deemed to fall within the scope of that claim. Moreover, in the following claims, the terms "first," "second," and "third," etc. are used merely as labels, and are not intended to impose numerical requirements on their objects.

[0315] Method examples described herein can be machine or computer-implemented at least in part. Some examples can include a computer-readable medium or machine-readable medium encoded with instructions operable to configure an electronic device to perform methods as described in the above examples. An implementation of such methods can include code, such as microcode, assembly language code, a higher-level language code, or the like. Such code can include computer readable instructions for performing various methods. The code may form portions of computer program products. Further, in an example, the code can be tangibly stored on one or more volatile, non-transitory, or non-volatile tangible computer-readable media, such as during execution or at other times. Examples of these tangible computer-readable media can include, but are not limited to, hard disks, removable magnetic disks, removable optical disks (e.g., compact disks and digital video disks), magnetic cassettes, memory cards or sticks, random access memories (RAMs), read only memories (ROMs), and the like.

[0316] The above description is intended to be illustrative, and not restrictive. For example, the above-described examples (or one or more aspects thereof) may be used in combination with each other. Other embodiments can be used, such as by one of ordinary skill in the art upon reviewing the above description. The Abstract is provided to comply with 37 C.F.R. §1.72(b), to allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. Also, in the above Detailed Description, various features may be grouped together to streamline the disclosure. This should not be interpreted as intending that an unclaimed disclosed feature is essential to any claim. Rather, inventive subject matter may lie in less than all features of a particular disclosed embodiment. Thus, the following claims are hereby incorporated into the Detailed Description as examples or embodiments, with each claim standing on its own as a separate embodiment, and it is contemplated that such embodiments can be combined with each other in various combinations or permutations. The scope of the invention should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

The claimed invention is:

1. An apparatus for insertion into a body lumen, the apparatus comprising:

an optical fiber pressure sensor comprising:

an optical fiber configured to transmit an optical sensing signal;

an ambient temperature compensated Fiber Bragg Grating (FBG) interferometer in optical communication with the optical fiber, the FBG interferometer configured to receive a pressure and modulate, in response to the received pressure, the optical sensing signal; and

a sensor membrane in physical communication with the FBG interferometer, the membrane configured to transmit the received pressure to the FBG interferometer.

* * * * *

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摘要(译)

在一个示例中，该文献公开了一种用于插入体腔的装置，该装置包括光纤压力传感器。光纤压力传感器包括配置成传输光学传感信号的光纤，与光纤光学通信的温度补偿光纤布拉格光栅（FBG）干涉仪，FBG干涉仪配置成接收压力并调制，以响应接收压力，光学传感信号和与FBG干涉仪物理连通的传感器膜，该膜配置成将接收的压力传输到FBG干涉仪。